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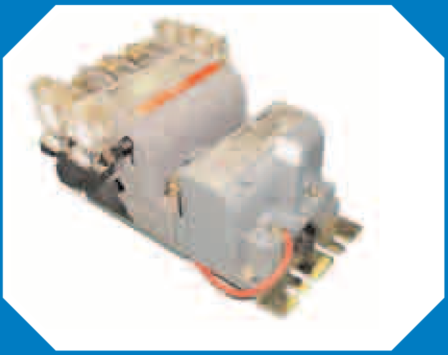

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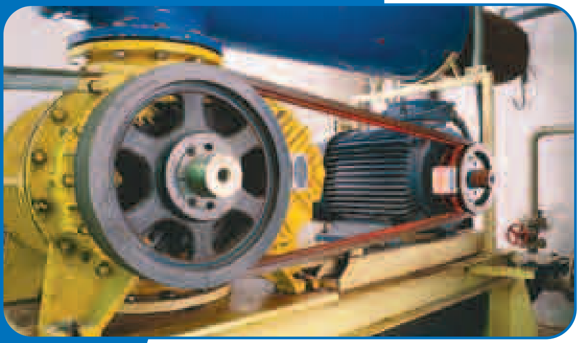

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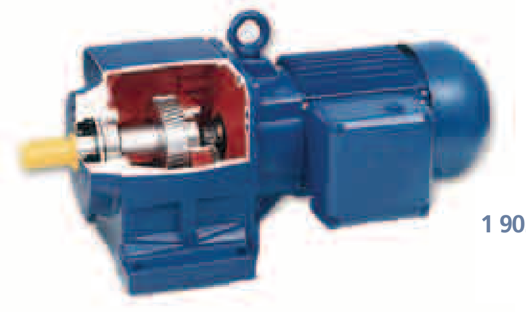

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INTRODUCTION TO ELECTRIC MOTORS DESIGN ENGINEERING

Robert Repas, Machine Design

Electric motors, both AC motors and DC motors, come in many shapes and sizes. Some are standardized electric motors for general-purpose applications. Other electric motors are intended for specific tasks. In any case, electric motors should be selected to satisfy the dynamic requirements of the machines on which they are applied without exceeding rated electric motor temperature. Thus, the first and most important step in electric motor selection is determining load characteristics - torque and speed versus time. Electric motor selection is also based on mission goals, power available, and cost.

Starting and running torque are the first parameters to consider when sizing electric motors. Starting torque requirements for electric motors can vary from a small percentage of full load to a value several times full-load torque. Starting torque varies because of a change in load conditions or the mechanical nature of the machine, in which the electric motor is installed. The latter could be caused by the lubricant, wear of moving parts, or other factors.

Electric motors feature torque supplied to the driven machine which must be more than that required from start to full speed. The greater the electric motor's reserve torque, the more rapid the acceleration.

Electric motor drive systems that use gear reducers have parts that rotate at different speeds. To calculate acceleration torque required for these electric motors, rotating components must be reduced to a common base. The part inertias are usually converted to their equivalent value at the drive shaft. Equivalent inertia $W_2K_2{}^2$ of the load only is found from:

$$W_2K_2{}^2 = (W_1K_1{}^2)(N_1/N_2)^2$$

where $W_1K^2{}_1$ = load inertia in lb-ft^2, N_1 = load speed in rpm, and N_2 = electric motor speed in rpm.

Electric motors have bodies which have a straight-line motion are often connected to rotating driving units by rack-and-pinion, cable, or cam mechanisms. For these electric motor parts, the equivalent WK2 is found from:

$$WK^2 = W(S/2N)^2$$

where W = load weight, S = translation speed in fpm, is pi, and N = rotational speed in rpm.

ELECTRIC MOTORS - ACCELERATION TIME:

Acceleration time for electric motors is directly proportional to total inertia and inversely proportional to the electric motor torque. For electric motors with constant acceleration torque, acceleration time is:

where WK^2 = rotational inertia in lb-ft^2, $(N_2 - N_1)$ = the speed difference, and T_x = acceleration torque in lb-ft. For translating bodies, acceleration time is:

$$\frac{t = WK^2\ (N_2 - N_1)}{308\ T_x}$$

where W = weight of the load in lb, $(S_2 - S_1)$ = the translation speed difference, and F_x = translation force in lb.

$$\frac{t = W\ (S_2 - S_1)}{1{,}932\ F_x}$$

An approximation method is necessary to find the electric motor's acceleration time if acceleration torque is not linear during speed increase. The quickest method is to break up the speed versus torque curves of the electric motor and the driven machine into segments and calculate acceleration time for each segment. Accurate electric motor acceleration times usually result.

ELECTRIC MOTORS - POWER RATING:

Electric motors offer the horsepower required to drive a machine, which is typically referred to as electric motor load. The most common equation for power-based electric motors on torque and rotational speed is: hp = (torque X rpm)/5,250.

If the electric motor's load is not constant and follows a definite cycle, a horsepower versus time curve for the driven machine is helpful. From this curve, both peak and rms the electric motor's horsepower can be determined. Rms load horsepower indicates the necessary continuous electric motor rating. Peak load horsepower is not necessarily an indication of the required electric motor rating. However, when a peak load is maintained for a period of time, electric motors feature a rating, which usually should not be less than peak load horsepower.

DUTY CYCLE - ELECTRIC MOTORS:

Continuous steady-running loads over long periods are demonstrated by fans and blowers. On the other hand, electric motors installed in machines with flywheels may have wide variations in running loads. Often, electric motors use flywheels to supply the energy to do the work, and the electric motor does nothing but restore lost energy to the flywheel. Therefore, choosing the proper electric motor also depends on whether the load is steady, varies, follows a repetitive cycle of variation, or has pulsating torque or shocks.

For example, electric motors that run continuously in fans and blowers for hours or days may be selected on the basis of continuous load. But electric motors located in devices like automatically controlled compressors and pumps start a number of times per hour. And, electric motors in some machine tools start and stop many times per minute.

Duty cycle is a fixed repetitive load pattern over a given period of time which is expressed as the ratio of on-time to cycle period. When operating cycle is such that electric motors operate at idle or a reduced load for more than 25% of the time, duty cycle becomes a factor in sizing electric motors. Also, energy required to start electric motors (that is, accelerating the inertia of the electric motor as well as the driven load) is much higher than for steady-state operation, so frequent starting could overheat the electric motor.

For most electric motors (except squirrel-cage electric motors during acceleration and plugging), current is almost directly proportional to developed torque. At constant speed, torque is proportional to horsepower. For accelerating loads and overloads on electric motors that have considerable droop, equivalent horsepower is used as the load factor. The next step in sizing the electric motor is to examine the electric motor's performance curves to see if the electric motor has enough starting torque to overcome machine static friction, to accelerate the load to full running speed, and to handle maximum overload.

ELECTRIC MOTORS - SERVICE FACTORS:

A change in NEMA standards for electric motor service factors and temperature rise has been brought about because of better insulation used on electric motors. For instance, a 1.15 service factor - once standard for all open electric motors - is no longer standard for electric motors above 200 hp.

Increases in electric motor temperature are measured by the resistance method in the temperature rise table. Electric motors feature a nameplate temperature rise which is always expressed for the maximum allowable load. That is, if the electric motor has a service factor greater than unity, the nameplate temperature rise is expressed for the overload. Two Class-B insulated electric motors having 1.15 and 1.25 service factors will, therefore, each be rated for a 90°C rise. But the second electric motor will have to be larger than the first in order to dissipate the additional heat it generates at 125% load.

Electric motors feature a service factor, which indicates how much over the nameplate rating any given electric motor can be driven without overheating. NEMA Standard MGI-143 defines service factor of an ac motor as "...a multiplier which, when applied to the rated horsepower, indicates a permissible horsepower loading which may be carried under the conditions specified for the service factor..." In other words, multiplying the electric motor's nameplate horsepower by the service factor tells how much electric motors can be overloaded without overheating. Generally, electric motor service factors:

* Handle a known overload, which is occasional.

* Provide a factor of safety where the environment or service condition is not well defined, especially for general-purpose electric motors.

* Obtain cooler-than-normal electric motor operation at rated load, thus lengthening insulation life.

ELECTRIC MOTORS - EFFICIENCY:

Small universal electric motors have an efficiency of about 30%, while 95% efficiencies are common for three-phase machines. In less-efficient electric motors, the amount of power wasted can be reduced by more careful application and improved electric motor design.

Electric motors feature an efficiency level which also depends on actual electric motor load versus rated load being greatest near rated load and falling off rapidly for under and overload conditions.

AC DRIVES OFFER OPPORTUNITIES TO REDUCE MAINTENANCE COSTS

Doug Weber, marketing manager, Allen-Bradley Drives Business, Rockwell Automation

Many users of AC drives are aware of the significant reduction in energy consumption that is offered when an AC drive is used to control the speed of a centrifugal fan or pump. Using a drive to operate these devices at, for example, 80 percent of their rated speed can cut energy costs in half.

What is often overlooked is the far-reaching impact on the overall health of automated systems that AC drives can offer. In fact, converting a process from fixed speed to variable speed in itself can reduce wear and tear and reduce maintenance requirements for mechanical systems by reducing start/stop cycles and eliminating vanes, dampers, valves and other mechanical system components. In addition to these benefits, understanding the features offered by a variable speed drive can significantly reduce system maintenance and reduce overall operating costs.

MONITORING

Drives have somewhat limited monitoring capabilities compared to devices exclusively dedicated to preventative maintenance. By nature, however, they do monitor motor current and speed and can perform protective functions based on that information. Programmable Logic Controllers (PLCs) and other controllers, when connected to a drive via a communications network, can also monitor these values and provide warnings and reminders to maintenance personnel that something in the process has changed. For example, by monitoring the motor current and speed, it may become obvious that a motor is loaded more heavily than normal and that the mechanical system should be checked before a failure occurs.

MOTOR OVERLOAD

In more extreme situations, the drive itself will act to protect the motor. Almost all drives today have a built-in electronic motor thermal overload feature. When a motor is in a state of severe exertion, beyond its safe operating limits, the motor overload feature can reduce the output current or shut off the motor and protect it from thermal damage or catastrophic failure. Motor overload software uses an algorithm incorporating motor current, speed, and time as inputs to model the temperature of the motor.

This may also be done with thermister feedback directly from devices buried in the motor windings, using actual temperature readings to determine motor stress. Multi-motor applications – those using one AC drive and more than one motor – will require the motor overload to be disabled since the drive would be unable to distinguish each individual motor's current to provide protection for individual motors. These applications require more advanced machine monitoring devices that can accept data from multiple sources to alert personnel of impending faults and failures.

S CURVE

S Curve and controllable acceleration and deceleration are other, often-overlooked drive features that help improve process performance and reduce maintenance. When a load transitions from steady state speed to accelerating or decelerating, the transition is usually instantaneous. The same is true when the transition is reversed. While not as dramatic, it is the industrial equivalent of "popping the clutch" on a stick-shift car. This jerking action puts considerable stress on mechanical components. In belt-driven systems, belts can fly off or break. In geared systems, the process can wear or break gear teeth.

AC drives can control this phenomenon through a feature called S Curve. Using the same analogy, it is the process equivalent of "feathering or slipping the clutch" to ease into acceleration or deceleration. S Curve controls the jerk, or rate of change of acceleration. It has long been recognized as an aid in the handling of very light conveyor loads, such as in a bottling line, but it can also play a significant role in extending the life of mechanical components. Lower mechanical stress means lower maintenance costs.

FLYING START

The Flying Start feature is used to reconnect the drive to a motor that is already spinning and, as quickly as possible, resume normal operation with minimal impact on load or speed. When a drive executes a normal start, it initially applies 0 Hz and ramps up to the commanded frequency. If the drive is started in this mode with the motor already spinning, large currents will be generated and an overcurrent trip may result if the current limiter does not react quickly enough. The likelihood of an overcurrent trip is further increased if there is a residual flux on the spinning motor when the drive starts. Even if the current limiter is fast enough to prevent an overcurrent trip, the end result is still to effectively decelerate the motor to a very slow speed and then reaccelerate it to the desired frequency. This can place extreme mechanical stress on the application, potentially causing costly downtime and repair costs while decreasing productivity.

In Flying Start mode, the drive's response to a start command will be to identify the motor's speed and begin its output synchronized in frequency, amplitude and phase to that of the spinning motor. The motor will then be reconnected at its existing speed and smoothly accelerated to the commanded frequency. This process eliminates overcurrent tripping and significantly reduces the time for the motor to reach its desired frequency. Since the motor is "picked up" smoothly at its rotating speed and ramped to the proper speed, little or no mechanical stress is present.

In some applications, such as large fans, wind or drafts may rotate the fan in the reverse direction when the drive is stopped. Flying Start will determine not only the speed of the fan, but also its direction of rotation. It will then execute controlled deceleration to zero and reacceleration in the commanded in the system.

SKIP FREQUENCY

Some machinery may have mechanical resonance points that must be avoided to minimize the risk of equipment damage. Let's use another automotive analogy. Many of us have experienced a severe "shimmy" in the steering wheel because the car's front end is out of alignment. Experience shows us that this shimmy can be severe at one speed, but speeding up or slowing down by just a few MPH will make the vibration stop. The car's misaligned front end has a mechanical resonance only at specific speeds. All rotating mechanical systems have these resonant points and many can be damaged if allowed to operate continuously at these speeds, causing system downtime and increased maintenance costs.

Drives offer a feature called skip frequencies or Critical Avoidance Frequencies to ensure that the motor will not continuously operate at one or more of these vibration points

The frequency that causes the resonance is programmed into the skip frequency parameters, and a bandwidth is programmed around the frequencies to create a skip band that avoids the vibration-causing areas. Most drives offer multiple skip frequency parameters to accommodate different resonance points.

Normal acceleration and deceleration are not affected by the skip frequencies. The drive output will ramp through the band uninterrupted. When, however, a command is issued to operate continuously inside the established band, the drive will alter the output to remain outside the band until a new command is issued.

When mechanical resonant frequencies are identified and drives are programmed to avoid continuous operation at those frequencies, wear and stress from vibration are greatly reduced.

CURRENT LIMIT

An AC drive has control of the amount of current it supplies to a motor. Current limiting functions are often used to prevent mechanical damage. By limiting current or shutting down the operation, AC drives can reduce mechanical damage. In addition to current limiting to reduce torque, most Allen-Bradley drives have a feature called an electronic shear pin – a modern take on an old concept. Outboard boat motors, for example, are usually equipped with mechanical shear pins. If the propeller strikes the bottom of the lake, rather than break the prop, the shear pin breaks, mechanically disconnecting the propeller from the motor and saving the mechanical system (and the boat owner's pocketbook). Similarly, a drive's electronic shear pin feature can define a current limit level that would cause damage. If the torque in the motor ever exceeds the set limit, the drive will automatically shut off the motor.

By limiting torque to a set level, AC drives provide good protection for systems that can become jammed, such as chain conveyors. By not allowing a motor to power through the jam, chain breakage and other damage can be avoided.

TORQPROV

In addition to features that limit torque or set "shear pin" torque levels, the Allen-Bradley PowerFlex 700 AC drive has a TorqProv algorithm especially for applications that require coordination between a motor and a mechanical brake. Prior to releasing a mechanical brake, the drive checks the motor output phase continuity and verifies proper motor control (torque proving). The drive will also verify that the mechanical brake has control of the load prior to releasing drive control (brake proving). After the drive sets the brake, motor movement is monitored to ensure the brake's ability to hold the load. This functionality can be very useful in lifting applications because it reduces the risk of dropping a load or damaging mechanical equipment. In addition, coordinating the drive and brake action reduces wear on the mechanical brake because in normal operation the motor is stopped before the brake is applied.

SPREADING THE WORD

Taking advantage of these drive features doesn't require a great deal of special training of plant personnel. Users need only be aware of the features and the benefits that the drives provide. By taking full advantage of the wide array of techniques already available, plant engineers can minimize the stress and abuse placed on valuable plant machinery, increase equipment uptime and reduce maintenance costs – key elements for boosting the bottom line. Plus, maintenance personnel will welcome the change as their jobs become less hectic with a little help from an unexpected source – the AC drive.

ADVANCES IN DRIVE TECHNOLOGY MEET TODAY'S DEMANDING APPLICATION REQUIREMENTS

Jon Simons, technology leader, Drives Business, Rockwell Automation

The last decade has witnessed remarkable transformation in variable frequency drive technology, including AC vector drive performance; expanded communications capabilities; smaller, more compact design; and integrated control capability driven by more powerful and faster microprocessors. Drive users can now optimize drive performance to meet a wide range of application requirements without the added cost of customization or complex programming. New technologies also give users the ability to satisfy their growing and varying needs, from standalone drives to complex, integrated systems.

VECTOR CONTROL DELIVERS RESULTS

Perhaps the biggest breakthrough over the past 10 years was the addition of vector control to AC drives. At the center of this technology is the use of a field-oriented control scheme that replaces a volts-per-hertz regulator core, found in most AC drives, with a high bandwidth current regulator that allows independent speed and torque control, while dynamically adapting to motor and load changes. The ability to identify flux and torque separately allows the drive to continuously regulate those same quantities in the motor, resulting in more precise and improved overall motor performance, including the ability to optimize efficiency.

Drive manufacturers continue to improve the performance capabilities of vector control AC drives, taking advantage of progress being made in microprocessor technology. Improved field-oriented control algorithms help optimize drive performance to meet the speed or torque requirements of the application. This enabled high-powered AC drives to outperform DC drives, including delivering torque independent of motor speed, with a quick reaction to shock loads. As a result, field-oriented control of AC drives combines the best advantages of DC drives – constant torque down to zero speed – with the best of the AC drives – simplified installation, tuning and maintenance.

In hoist and crane applications, tight demands on torque response require the drive to deliver high torque levels without losing control of the load and the ability to stop the load accurately and precisely. Likewise, applications such as mixers, centrifuges and extruders require a drive capable of delivering full torque immediately upon startup, constant torque throughout the operating speed range, and full torque down to zero speed. This helps ensure that an injection molding machine, for example, will generate proper material flow and produce high quality parts from the start, while minimizing scrap. For years, users relied on DC drives to meet these challenges, but users are now taking advantage of vector control AC drives that deliver a cost-effective, high-performance alternative.

INTEGRATED CONTROL CAPABILITIES

Other advances in drive technology center around logic control capabilities. These control features allow users to optimize general-purpose drives for specific applications without having to order a special drive or write additional code in a separate processor.

Because the embedded control is tightly coupled, users achieve higher speed and throughput. For example, users may be able to position-synchronize a printing press to boost throughput, or more quickly and precisely move items within a work cell, such as lifting and moving vehicle parts on an automotive assembly line.

By embedding the logic right into the drive, users also can reduce the size of the drive-control package, and improve reliability by minimizing the number of required connections. While applications with large I/O requirements may still require a separate controller, many simple processes can benefit from the improved speed and efficiency of a standalone drive unit.

DRIVES AND POSITIONING APPLICATIONS

Another significant advance in AC drive technology is their use in applications that require precise positioning during production. In the past, AC drives weren't designed to place products and materials with the accuracy required to be effective. Although high performance drives can sometimes match the accuracy of servo motion technology, more commonly, today's drives are replacing older mechanical systems, such as those on assembly lines.

For example, the Ford Motor Company's St. Paul, Minn., plant recently replaced hydraulic and mechanical transfer systems on the assembly line producing Ford Ranger plants with Allen-Bradley PowerFlex 700S drives from Rockwell Automation. The drives contain an embedded controller, DriveLogix, that enables the drive to meet the exact positioning requirements of the assembly line. Using the PowerFlex 700S and Point-to-Point Positioning Application software, the drives direct the truck frames to exactly the point needed on the assembly line, streamlining production and reducing maintenance associated with complex mechanical systems.

EASE OF USE TAKES PROMINENCE

As microprocessors continue to get faster, more powerful and less expensive, drive manufacturers will continue to look for ways to reduce the size, cost and complexity of AC drives, while enhancing performance. On the performance side, new techniques allow higher bandwidths of control even when faced with machine resonances. Still, while some end users demand more application versatility and flexibility, others need ease-of-use features, rather than technological advances.

One of the biggest areas of technology innovation is occurring in the area of drive programming and configuration, where simplification and ease of use is driving the developments. The use of programming wizards for drive startups is fast becoming a key area of focus. These tools operate much like the setup programs in new PCs, where after a few prompts, the wizard automatically installs the software and required drivers, sets all the parameters and recognizes the hardware devices that are plugged into the PC.

For example, new drive programming wizards will prompt the user for information about the application, size of the motor, and other critical information. It will then automatically set up all the parameters to meet the defined application and hardware requirements.

For more complex installation, like a centrifuge or lifting processes, the wizard might request some additional parameters, such as the type of application, the speed of the process, and the weight of the load. It will then automatically adjust the parameters to optimize the drive for that application. These tools can dramatically reduce drive startup and commissioning time and improve setup accuracy by eliminating a significant amount of manual configuration.

One consequence of increased connectivity is that individual devices will no longer be viewed and managed as isolated components, but rather as part of an integrated system. That's because users will be able to program, control and troubleshoot drives, controllers, relays, I/O and motion devices from a common interface using a single software package. This includes the ability to add logic using common software tools with the same look and feel — no matter whether the application involves a small drive in a standalone process, or a high-performance drive as part of a large PLC-based, integrated and networked system.

In addition to reduced setup and operational costs, a key benefit of this integrated environment is that users will be able to easily save all of their drive parameters and control logic in a single database. In the event of a failure, replacement and restoration of the original drive parameters would be a relatively simple process.

The proliferation of high-speed Ethernet and wireless networks on the plant floor enables users to continually increase the ability to monitor and control drives and share information. New technologies such as time synchronized services in Ethernet will provide even higher levels of control. The drive can then become an “information window” to the production process

TORQPROVE PROVIDES DIRECT CONTROL FOR HEAVY LOADS

Starting a motor improperly can waste energy and cause undue stress on mechanical components. The ability to stop a motor smoothly and precisely is equally important, particularly when moving heavy loads. To ensure smooth, precise stopping of its motors, Custom Powder Systems, an OEM that designs and builds customized lift equipment for the solid dosage pharmaceutical industry, recently upgraded to the Allen-Bradley PowerFlex 700 Vector Control AC drive with TorqProve. The solution replaced an open-loop drive system that used programmable controllers to issue all start/stop and mechanical brake commands.

The new solution tightened control between the brake and drive and simplified machine design by reducing controller wiring and programming time associated with configuring a separate controller. In fact, the machine can now be commissioned in minutes rather than hours. A programmable controller is still used, but controls only start/stop commands and speed control rather than trying to manage the entire process.

Additionally, because the drive controls the brake, commissioning is more precise and repeatable, reducing the impact of general mechanical wear on the brake thus allowing consistent performance throughout the life of the machine. In encoderless lifting and hoisting applications, the timing of drive starts/stops and brake control is critical. Brake wear has big impact on this timing. The TorqProve technology helps take the brake wear factor out of the equation because the timing is much tighter, more precise, easier to set up, and built in to the technology.

Moreover, the OEM's customers are more profitable and productive since load drops or misalignments due to brake wear or set-up issues are virtually eliminated, and Custom Powder Systems has saved money by reducing set-up time, warranty charges, and maintenance costs.

Improved diagnostics is another feature applied to newer drives as maintenance practices continue to be more proactive. For example, with current technology, users typically have a small window of time (a few minutes) until the drive will trip as a result of an overload condition. Enhanced thermal regulators extend this time by optimizing the IGBT switching patterns during periods of thermal stress. The new diagnostic tools will allow users to perform a trend analysis over longer periods of time to show that a drive may be drawing more current than normal to achieve the same speed.

With access to more detailed information over longer periods of time, users will be able to potentially predict problems and prevent catastrophic failures. Moreover, the improved quality and availability of data will enable maintenance personnel to be better positioned to troubleshoot, helping to reduce costs and improve uptime. Simple descriptions are given to pinpoint problems, not obscure fault codes.

CONCLUSION

Advances in AC drive technology are helping manufacturers increase productivity and save energy throughout their facilities. Increases in technology that delivers more precise speed and torque, as well as enhanced communications capabilities, reduce downtime and increase throughput, as well as give a more accurate picture of the manufacturing environment.

Also, as drives manufacturers continue to pack more performance into smaller packages, end users will have greater flexibility in selecting the right drive to meet future application needs. And with simplified setup tools, improved diagnostics and increased networking capabilities, users will have greater opportunities to maximize the return on their drive technology investments.

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For additional information Allen-Bradley drives from Rockwell Automation, visit www.rockwellautomation.com/drives.

AUDIBLE NOISE AND LOSSES IN VARIABLE SPEED INDUCTION MOTOR DRIVES WITH IGBT INVERTERS

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1. INTRODUCTION

The use of variable speed drives has gained increasing importance during recent years. For small and medium sized drives, PWM voltage source inverters are the standard type of equipment nowadays. Until a few years ago, the highest switching frequencies available were offered by Power-MOSFET inverters. However, their rated power was modest. Bipolar transistors could be used for higher power rating, but had a lower stitching frequency, The IGBT based inverters combine the advantages of both power electronic components: High switching frequency and high power ratings. Power ratings up to several hundreds of kVA are available commercially. The switching frequency may be several kHz.

Manufacturers claim that the increased switching frequencies lead to lower additional losses, due to the harmonics of the supplied voltage. Therefore, derating the motor at rated speed would not be required. Furthermore, the low harmonic content would avoid audible noise problems.

This article describes a large number of experiments comparing audible noise, losses and efficiency of induction motors supplied by an IGBT inverter or directly from the mains. The switching frequency of the IGBT PWM inverter is varied in order to study the influence of this parameter on the motor behavior. Furthermore, two motors are compared. The first motor is a standard induction motor with cast aluminum double squirrel cage rotor. The second motor has a copper cage, with round bars to avoid current redistribution; furthermore the bars are insulated with respect to the rotor iron in order to avoid extra losses, which are difficult to incorporate in the theoretical analysis.

II. AUDIBLE NOISE

Audible noise has been of concern for users and manufacturers of inverter supplied induction motors since their introduction. The first developments using thyristors and high power GTO inverters may be particularly noisy. Using an appropriate switching pattern can resolve part of the problem, but still audible noise increases of 10 to 15 dB(A) or more are noticed, both for small and medium sized drives [1,2,3]. The analysis using rotating field theory shows that the PWM switching pattern clearly influences the audible noise level. At higher fundamental frequencies however, the degree of freedom for choosing the PWM pattern is limited. In order to get the maximum output voltage, the voltage pattern is very close to a rectangular shape, independent of the switching frequency.

The theoretical analysis of the audible noise starting from the design parameters of the motor, especially the number of stator and rotor slots, and the frequency spectrum of the voltage supplied by the inverter, yields its frequency spectrum. It is shown that the transition of the PWM pattern is the most important factor in the audible noise. Furthermore, the analysis shows under which circumstances pure tones in the spectrum of the audible noise may be expected. This is very important as the human ear is very susceptible to these pure tones: the same audible noise level is experienced being 10 dB(A) higher when it contains pure tones.

III. LOSSES

Due to the harmonics in the inverter voltage and current, the losses in the rotor increase as a result of the skin effect [5]. The currents induced by the higher voltage harmonics are concentrated in the upper part of the rotor bars. Therefore, the efficiency decreases due to these losses. In conventional inverter supplied drives using low switching frequencies, these extra losses are high and the manufacturers of drives prescribe generally a 10% derating of the motor in order to limit excessive heating. However, practical experiments showed that a 10% derating sometimes is not sufficient [5,6,7].

The higher switching frequency of modem inverters lead to a lower harmonic content, especially at low speeds. Therefore, the increase in the losses is less pronounced at low speed. However, in pump and fan drives, the output power is limited at low speed. Therefore, the efficiency gain is large, without yielding large power or energy savings. If a constant torque as a function of speed has to be delivered to the load, the power is proportional to the speed. The gain is larger at lower speed than in pump and fan drives.

IV. MOTOR AND INVERTER USED

The first motor used is a standard 22 kW machine with a double cage rotor. The rotor has double bar construction. The rotor bars are made in cast aluminum. These bars are not insulated with respect to the rotor iron, leading to supplementary losses due to interbar currents. This type of rotor construction is required in order to increase the starting torque when connecting the motor directly to the supply. The rotor slots are skewed.

As these starting problems are not present in inverter supplied machines, a motor with no current redistribution is no real problem and would lead to less additional losses if the motor is supplied with a non sinusoidal voltage. In order to assess the influence of the current redistribution in the rotor, a special rotor for a standard 13.5 kW machine is built with round rotor bars. The area of the rotor bars is chosen in such a way that the torque and the losses at rated speed are the same as in the standard design. Copper is used as the material for the bars. Interbar currents are avoided by insulating the bars with respect to the rotor iron. The number of rotor bars is kept the same and the stator is a standard construction. No skewing is applied. Both standard rotor design and new rotor are accounted for in the analysis. The inverter is a standard inverter with IGBTS. The switching frequency of the components can be chosen from I to 12 kHz. The tests are done in the normal operation mode, i.e. keeping the Volts/Hertz ratio constant. As a comparison the motors are directly coupled to the mains. The use of a pure sinusoidal supply yields an absolute target for inverter manufacturers, as this is the ultimate optimum regarding frequency content. Using these combinations, the influence of the most important parameters on both losses and audible noise is studied.

V. MEASURING SET-UP

The measuring set-up consists of an inverter supplied induction motor, with combinations as discussed above. The machine is loaded with an eddy current brake that can be controlled accurately in order to load the motor as prescribed. If a pump, fan or compressor characteristic is to be implemented, the mechanical output torque is proportional to the square of the speed, otherwise the torque is kept constant with respect to the speed (elevator or crane drive). The overall lay-out and most important components of the measuring set-up are shown in Fig. 1.

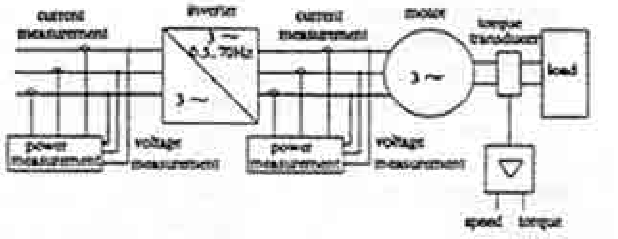


Figure 1

The audible noise was measured in a semi-anechoic chamber, avoiding interference of the frequency inverter audible noise. The load has a very low audible noise level due to special bearings and water cooling. The audible noise is measured using a condenser microphone. Both the overall noise level in dBlin or dB(A), and its frequency spectrum are registered.

A torque transducer is used to couple both machines. The transducer contains strain gauges that are linked with the stationary recording equipment using a frequency modulated transmitter system. These measurements yield a very high accuracy of the torque, far better than the reaction torque often used as an alternative. Also non-steady state torque components and torsional vibrations may be accounted for. In the torque transducer a speed transducer is incorporated, yielding the mechanical power by multiplication. The accuracy of the output power is better the 0.5 %.

The input -power is measured with an accuracy of 0.2 % using special power, voltage and current measuring equipment

For the assessment of the electrical power between the inverter and the motor, special attention has to be paid to the equipment used. The harmonics in both current and voltage prevent the use of standard power measuring equipment. The frequency spectrum of the power measuring equipment goes up to 200 kHz, in order to account for the power produced by the higher harmonics. The accuracy of the power between inverter and motor is 0.5 %.

All efficiency measurements are carried out after thermal equilibrium is reached in the motor. Therefore the motor is loaded during more than one hour with rated power at rated speed before the experiments are started. In the specially designed machine the temperature is monitored and measured using Pt-100 (Platina resistors) sensors.

At rated speed and load, the temperature when supplying the motor with the inverter is compared with the temperature when the motor is coupled directly with the supply, in both cases loaded with rated power. The temperature gives a direct indication of the required derating, if any.

VI MEASUREMENTS AND CONCLUSIONS

A. OVERALL AUDIBLE NOISE LEVEL

The overall audible noise level was measured for the 22 kW motor loaded with 100 Nm. In Fig. 2 the overall audible noise level is presented as a function of the switching frequency and this for different fundamental frequencies (15-25-40-45-50-70 Hz).

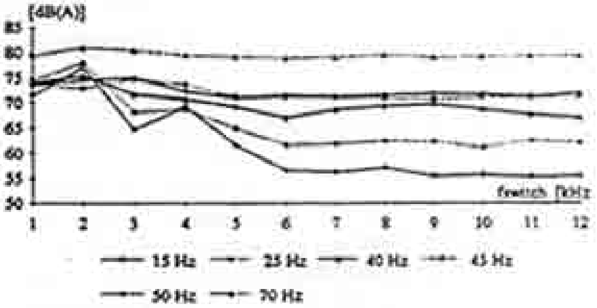


Figure 2

CONCLUSIONS:

- At a switching frequency of 2 or 4 kHz, the overall audible noise level is higher than expected in the case of a fundamental frequency of 40 Hz. This is due to the interference between the natural frequency of the stator and the frequency of one of the vibrations produced by the electromagnetic forces caused by the switching frequency. These frequencies should be avoided. At higher frequencies, these phenomena do not occur because of the difference between the set-up switching frequency and the real switching frequency used in the inverter.
- Generally, the overall audible noise level decreases if the switching frequency increases. Particularly, up to 6 kHz there is a huge drop in the audible noise. Once the switching frequency is above 6 kHz, the overall audible noise level is stabilized because the number of switching harmonics in the audible noise region strongly decreases.
- At higher fundamental frequencies, thus at higher motor speeds the overall audible noise level decreases less if the switching frequency increases, because the fan audible noise dominates the motor audible noise.
- At lower motor speeds, the overall audible noise is strongly reduced by applying higher switching frequencies.
- Generally, the audible noise increases with the increasing fundamental frequency. But at 50 Hz, the motor produces less audible noise than when supplying the motor with 45 Hz

because the motor design is optimized for a 50 Hz supply by an appropriate choice of the number of stator and rotor bars.

When comparing 50 Hz sinus main supply and 50Hz inverter supply, there is only a difference of 1 dB(A) due to the harmonics.

B. AUDIBLE NOISE SPECTRUM

The audible noise spectrum is analyzed to see if there are any pure tones in the spectrum, as the human ear is very susceptible for such tones.

Several audible noise spectra have been analyzed for both motors. Only two spectra will be discussed here: the spectrum for the 22 kW motor at a fundamental frequency of 5 Hz, a switching frequency of 6 kHz and a load of I 00 Nm (Fig. 3) and the spectrum for the 13.5 kW motor at a fundamental frequency of 45.05 Hz, a switching frequency of 5 kHz and a load of 75 Nm (Fig. 4).

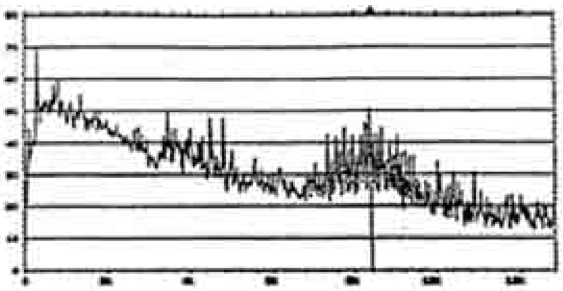


Figure 3. Audible noise spectrum of the 22 kW motor, fundamental frequency = 50 Hz, switching frequency = 6 kHz, load = 100 Nm.

The switching frequency is set-up to be 6 kHz but the real switching frequency used in the inverter is 8400 Hz, as can be clearly seen in Fig. 4 where there is an increase in audible noise of 25 dB(A) around 8400 Hz

There is also a component of 70 dB(A) at 300 Hz. This pure tone is caused by the fifth harmonic of the current at 250 Hz. The frequency difference between the resulting audible noise at 300 Hz and the cause at 250 Hz can be explained as follows. The fifth harmonic of the current has a velocity of 250 Hz in the opposite direction of the velocity of the rotating field at 50 Hz. The relative velocity between the fifth harmonic and fundamental of the rotating field is 300 Hz. This gives torque pulsations at 300 Hz and thus audible noise is produced at 300 Hz. It should be mentioned that this pure tone only appears at a voltage of 380 V.

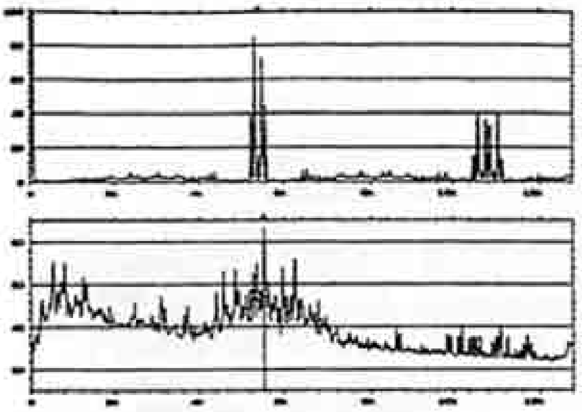


Figure 4. Voltage and audible noise spectrum of the 13.5kW motor, fundamental frequency = 45.05 Hz, switching frequency = 5 kHz, load = 75 Nm.

Around 5 kHz some large components appear in the audible noise. They are caused by space harmonics of the rotating field. These space harmonics cause vibrations and audible noise. If the frequency of the vibrations is the same as one of the natural frequencies of the stator, there is a large audible noise production.

The switching frequency is set-up to be 5 kHz, but the real switching frequency used by the inverter is .5406 Hz as can be seen in the voltage spectrum.

Because the motor bars are not skewed, the rotor harmonics are not suppressed so they yield a lot of vibrations. The frequencies of these vibrations may be calculated [8]:

$$f_t = 2f\left[\frac{N_2}{2p}|g_2|(1-s)\pm 1\right]$$

and

$$f_t = 2f\left[\frac{N_2}{2p}|g_2|(1-s)\right]$$

where

N_2	number of rotor slots;
p	number of pole pairs;
s	slip;
f	fundamental frequency.

In this case the motor has 28 rotor bars, a speed of 1318 t/min and 4 pole pairs. At a fundamental frequency of 45.05 Hz, the motor has a slip of 2.48%. Applying (1) and (2) for g2 = *9, one can calculate that there should be vibrations at 5626 Hz, 5445 Hz and 5563 Hz.

At 5536 Hz there is also a resonance frequency of the stator. Therefore, at a fundamental frequency of 45.05 Hz and a speed of 1318 t/min there is a spike of 78 dB at 5536 Hz at all switching frequencies. At the switching frequency of 5 kHz as shown in Fig. 4 this spike is even 86 dB because of the interaction of a vibration caused by a winding harmonic and a vibration caused by a time harmonic of the voltage spectrum.

The harmonics of the voltage system cause vibrating forces, yielding audible noise. In the voltage spectrum of Fig. 4 there is a time harmonic at 5488 Hz. As the fundamental frequency is 45 Hz, the vibration frequency is 5533 Hz. Taking the accuracy of the measurements into consideration, this frequency equals the resonance frequency of the stator and with a vibration frequency caused by a winding harmonic.

The pure whistle tone of 86 dB in the audible noise spectrum of Fig. 4 is caused by the accidental coincidence of 3 effects at 5536 Hz:

- stator resonance;
- vibrations due to winding harmonics;
- vibrations due to switching harmonics.

Clearly, such a situation should be avoided by all means.

Generally, for all motors one can say that if there are voltage and current harmonics then audible noise harmonics will be generated. If the spectrum is optimized for instance by taking higher switching frequencies or by taking another pulsewidth modulation pattern, the audible noise level can be reduced. The fundamental wave can in some cases cause resonance and thus high audible noise levels, even if a sinusoidal supply is available. The switching frequency should be chosen in such a way that time harmonics do not yield vibration forces that match with mechanical natural frequencies of the stator.

C. LOSSES AND EFFICIENCY

The higher the chosen switching frequency, the better the spectrum supplied by the inverter. The harmonic currents induced in the motor become smaller. The motor voltage gets more and more sinusoidal. Therefore, the losses in the motor decrease. As the losses in the inverter are defined by the number of times the power electronic components have to operate, the losses in the inverter on the other hand increase with a higher switching frequency. Therefore an optimum switching frequency will exist.

The type of motor used is also important: motors experiencing a large amount of current redistribution in the rotor when supplied from the mains causing extra losses with inverter supply, as the high frequency currents are concentrated in the upper portion of the rotor bars. To analyze the influence of the rotor lay-out, two motors of the same rated power are compared (one with an aluminum skewed double cage rotor and one with a rotor having non skewed copper bars).

1) DEFINITION OF THE LOSSES AND EFFICIENCIES

The following losses and efficiency definitions are used:

- Fundamental power:

$$P_{fund} = U_{(1)} I_{(1)} \cos\varphi_{(1)} \qquad (3)$$

- Harmonic losses:

$$P_{harm} = P_{conv.out} - P_{fund} = \sum_{i=2}^{\infty} U_{(i)} I_{(i)} \cos\varphi_{(i)} \qquad (4)$$

- Motor losses:

$$P_{motor} = P_{fund} - P_{mech} \qquad (5)$$

- Inverter losses:

$$P_{conv} = P_{conv.in} - P_{conv.out} \qquad (6)$$

- Overall losses:

$$P_{tot} = P_{mech} - P_{conv.in} \qquad (7)$$

- Motor efficiency:

$$\eta_{motor} = \frac{P_{mech}}{P_{fund}} \qquad (8)$$

- Inverter efficiency:

$$\eta_{conv} = \frac{P_{fund}}{P_{conv.in}} \qquad (9)$$

- Overall efficiency:

$$\eta_{tot} = \frac{P_{mech}}{P_{conv.in}} \qquad (10)$$

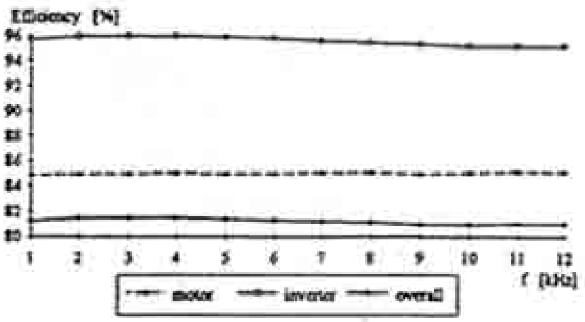


Fig. 5. Efficiencies as a function of the switching frequencies, for the 13.5 kW motor supplied with a fundamental frequency of 35 Hz and loaded with 70 Nm.

2) INFLUENCE OF THE SWITCHING FREQUENCY ON THE EFFICIENCY

The temperature is kept constant during the measurements. Again, several measurements were done, but only one measurement reported in detail. The efficiencies and the losses as a function of the switching frequencies for the 13.5 kW motor supplied with a fundamental frequency of 35 Hz and loaded with 70 Nm, are shown in respectively in fig. 5 and table I.

TABLE I
LOSSES AT 35 Hz AND 70 Nm

	Losses			
F switch [kHz]	motor [kW]	inverter [kW]	harmonic [kW]	overall [kW]
1	1.33	0.29	0.109	1.72
2	1.32	0.30	0.074	1.70
3	1.32	0.31	0.062	1.70
4	1.32	0.30	0.079	1.70
5	1.32	0.34	0.048	1.71
6	1.32	0.35	0.045	1.72
7	1.31	0.37	0.043	1.73
8	1.31	0.39	0.04	1.74
9	1.33	0.40	0.038	1.76
10	1.31	0.41	0.041	1.76
11	1.31	0.40	0.04	1.75
12	1.31	0.40	0.043	1.75

The following conclusions may be drawn:

- The motor losses are independent of the switching frequency.

- The inverter losses increase with increasing switching frequency.

- The harmonic losses decrease with increasing switching frequency. From 10 kHz on subharmonics appear and give rise to a slight increase of this loss component.

- The total losses reach a minimum around a frequency of 3 kHz.

In other operating points (different torque and different fundamental frequency) the overall losses are also minimum around 3 to 4 kHz.

A comparison is also made between the two different motors of 13.5 kW and between mains supply and inverter supply at 5OHz. The overall losses are represented in table II. In fig. 6 the different losses are represented as a function of the switching frequency.

TABLE II
Comparison Between the Losses of the Standard Motor and the New Motor (13.5kW)

Fswit (kHz)	Feff (kHz)	Standard Rotor Overall (kW)	New Rotor Overall (kW)
1	1.2	2.04	2.23
2	2.7	2.01	2.21
3	3.6	2.0	2.21
4	5.4	2.01	2.20
5	6.0	1.99	2.21
6	8.4	2.00	2.22
7	8.4	2.00	2.23
8	10.8	1.99	2.23
9	10.8	2.01	2.23
10	10.0	2.00	2.22
11	11.0	2.00	2.24
12	12.0	1.99	2.23
main supply		1.56	1.77

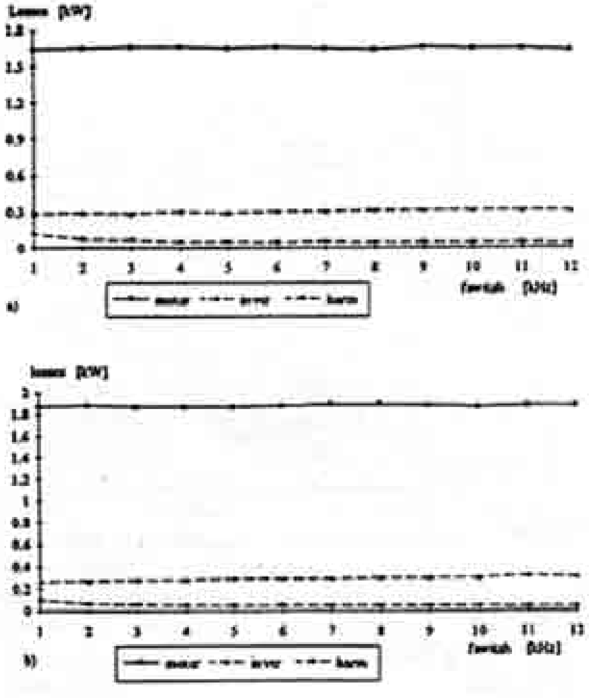


Fig. 6 Losses as a function of the switching frequencies, for the 13.5 kW motor supplied with a fundamental frequency of 50 Hz and loaded with 75 Nm.
a) Standard rotor
b) New motor

The following conclusions can be made:

- Both motors have almost the same harmonic losses. At lower switching frequencies (< 3 kHz) the standard motor has slightly higher losses.

- In both cases the inverter losses are comparable.

- The motor losses of the standard motor are smaller d= the motor losses of the new motor. This is due to the larger space harmonics in the air gap caused by missing skewing

- With a main supply, the overall losses are, in both cases, smaller than when an inverter is used.

The same measurements were repeated for the 22 kW standard motor and again the optimal switching frequency concerning the motor losses is found to be 4 kHz.

3) INFLUENCE OF THE U/F RATIO ON THE EFFICIENCY

There are several possibilities to set-up the voltage/frequency ratio. In this paper two of them are compared. U/f is a constant and U/f is dependent of the load (automatic)(Fig. 7).

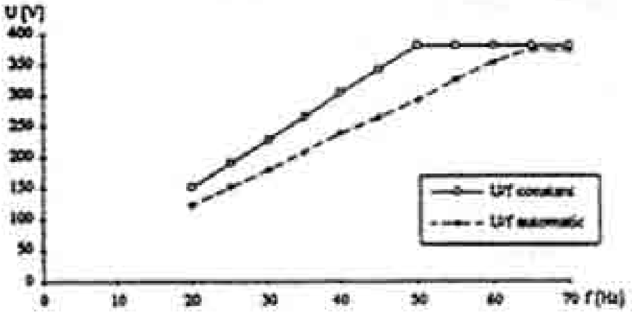


Fig. 7 U/f at T = 60 Nm and fswitch = 6 Hz

The lower voltage in the second case decreases the flux level and, therefore, less audible noise is produced. The harmonic losses are also lower because of the improved spectrum of the voltage but the motor losses are larger because the currents have to increase to match the required power. The inverter losses also increase. Other disadvantages are a decrease in speed and less dynamic response for torque variations.

D. MOTOR TEMPERATURE WHEN USING AN INVERTER

The manufacturers of the IGBT-inverters supply allowable torque versus frequency curves (fig. 8)

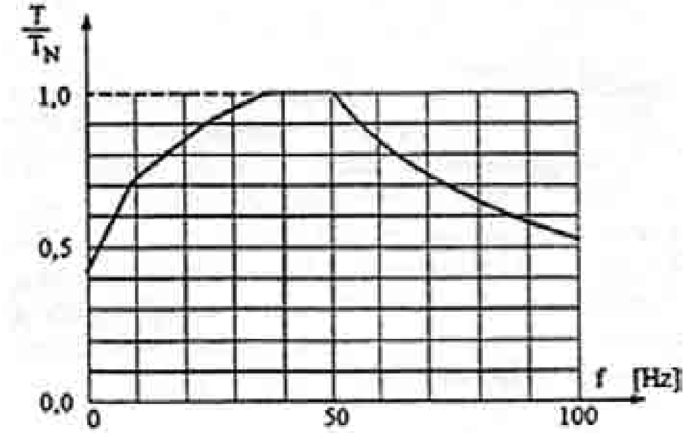


Fig. 8 Load curves for continuous load of IEC 34 motors Switching frequency 3 kHz.

These curves are valid if the fundamental frequency at the point of field weakening is 50 Hz. If the fundamental frequency is higher than 50 Hz, the torque decreases as the voltage is kept constant as the frequency rises. Therefore the flux and the torque decrease. At lower fundamental frequencies, the torque decreases due to a lack of cooling.

Therefore, with the inverter used between a fundamental frequency between 40 Hz and 50 Hz, the motor can deliver its rated torque. The temperature rise at a fundamental frequency should not be higher than with the main supply.

The temperature in the stator winding is measured with embedded Pt - 100 temperature sensors. Table III gives the temperate rise when the motor is operating at a fundamental frequency of 50 Hz, supplied by the inverter at a switching frequency of 3 Hz and 12 kHz and directly by the mains, at a load torque of 70 Nm.

TABLE III
TEMPERATURE RISE WITH INVERTER SUPPLY AND MAIN SUPPLY AT 50 Hz AND 70 Nm

stator slot	3 kHz	12 kHz	main supply
1	55.2	55.5	54.6
7	58.7	59.3	58.4
13	55.6	56.0	55.1
19	55.3	55.9	54.9
25	58.1	58.6	58.1
31	56.6	57.2	56.2
average	56.6	57.1	56.2

The following conclusions can be drawn:

- The temperature of the motor is independent of the switching frequency at a fundamental frequency of 50 Hz.
- The temperature of the motor directly connected to the mains does not differ much from the motor temperature when fed by a inverter.
- The optimum switching frequency of 3 kHz gives a slightly lower temperature rise.

The same measurements have also been done for other loads, yielding comparable results. It may be concluded that for the motor and inverter combination used is these tests derating is not necessary. It is dangerous to generalize this conclusion for all motor-IGBT inverter combinations because only the temperature in the stator is measured. Furthermore these measurements were carried out on a single squirrel-cage rotor motor with a specialty built rotor.

VII GENERAL CONCLUSIONS

The choice of the switching frequency has a large influence on the audible noise produced by induction motors. By taking higher switching frequencies, the time harmonics move to a non-audible region. At some higher switching frequencies, subharmonics appear, having a bad influence on the audible noise and, therefore, should be avoided. At higher fundamental frequencies, the audible noise of the fan dominates and the use of higher switching frequencies has practically no effect on the audible noise.

The switching frequencies can cause pure tones that are very disturbing to the human ear. Fundamental waves can also cause vibrations and audible noise. One should be careful that the vibration frequencies from fundamental waves and switching frequencies do not match the natural frequencies of the stator as otherwise the audible noise increases a lot.

The influence of the switching frequency on the efficiency is rather small. Minimal overall losses appear around 3 and 4 kHz.

The voltage-frequency ratio should be taken constant from the point of view of the efficiency.

VII REFERENCES

[1) R.Belmans, L.DHondt, A.Vandenput, W.Geysen: “Analysis of the audible noise of three phase squirrel cage induction motors supplied by inverters,” IEEE Trans. on Industry Applications, September-/October 1987, Vol.IA-23, pp.842-847.

[2) R.Belmans, D.Verdyck, W.Geysen, R.Findlay: “Electromechanical analysis of the audible noise of an inverter-fed squirrel-cage induction motor,” IEEE Transactions on Industry Applications, Vol-27, No.3, May/June 1991, pp.539-544.

[3] R.Belmans, W-Geysen, G.Bailly, P-K.Sattler: TheoreticaI and experimental analysis of the audible noise of an inverter fed squirrel cage induction motor,” International Conference on Electrical Machines (ICEM), Cambridge, Massachusetts, USA., August 13-15, 1990, pp.485-490.

[4] R.Belmans, D.Vcrdyck, T.-B.Johansson, W.Geysen: “Comparison of starting conditions of induction motors fed from an infinite bus and current source inverter using finite element calculations,” Proceedings of the Fourth European Conference on Power Electronics and Applications, Firenze, Italy, September 3-6, 1991, pp.2.375-2.378.

[5] R.Belmans, D.Vermeulen, A.Vandenput, W.Geysen: “Economy of the introduction of adjustable speed drives for pumps, fans and compressors,” Conference record on the 1986 IEEE-IAS Annual Meeting, September 28-October 3, 1986, Denver, U.S.A., pp.321-327.

[6] R. Belmans, D.Vermeulen, A.Vandenput, W.Geysen: “Techno-economical analysis of inverter fed pump drives,” Second European Conference on Power Electronics and Applications, EPE, 22-24 September 1987, pp. 1003-1008

[7] E.Lajoie-Maznec, D.Pratmarty: “Etat de l’offre europeene de convertisseurs de frequence pour machines asynchrones”, Electricite de France, Direction des Etudes et Recherches, Mars 1993

[8] P.L.Alger, “Induction Machines, Their Behavior and Uses,” Gordon and Branch Science Publishers, New York, London, Paris, 1970

MINIMUM REQUIREMENTS FOR ELECTRICAL MOTOR OPERATION AND MAINTENANCE

James Charles, Criterion

1.0 PURPOSE

The purpose of this Criterion is to establish the minimum requirements and best practices for operation and maintenance of Electrical Motors at LANL. This document addresses the requirements of LIR 230-05-01, “Operations and Maintenance Manual.” (Reference 10.1)

The implementation of these requirements satisfies DOE Order 430.1A, “Life Cycle Asset Management,” Attachment 2 “Contractor Requirements Document,” Paragraph 2, Sections A through C, which in part require UC to “… maintain physical assets in a condition suitable for their intended purpose” and employ “preventive, predictive, and corrective maintenance to ensure physical asset availability for planned use and/or proper disposition.” Compliance with DOE Order 430.1A is required by Appendix G of the UC Contract. (Reference 2)

2.0 SCOPE

The scope of this Criterion includes the routine inspection, testing and maintenance of Electrical Motors at all nuclear and non-nuclear LANL facilities.

2.1 ELECTRICAL MOTORS

Low voltage – 600 Volts and less, Alternating Current (AC) or Direct Current (DC), excluding motors with sleeve type bearings and fractional horsepower motors with factory sealed bearings. A typical selection criteria is motors that are 3 phase, 10 to 600 horsepower, and motors with ball-type bearings.

3.0 ACRONYMS AND DEFINITIONS

3.1 ACRONYMS

AR Administrative Requirements
CFR Code of Federal Regulations
CMMS Computerized Maintenance Management System
IR Insulation Resistance Test
LIR Laboratory Implementation Requirement
NEC National Electrical Code
NEMA National Electrical Manufactures Association
NFPA National Fire Protection Association
O&M Operations and Maintenance
PI Polarization Index Test
PP&PE Personal Property and Programmatic Equipment
PPE Personal Protective Equipment
RP&IE Real Property and Installed Equipment
SEM Systems, Engineering and Maintenance
SSC Structures, Systems, and Components
UC University of California
VOM Voltage/Ohmeter

3.2 DEFINITIONS

3.2.1 CONTINUOUS DUTY

A requirement of motor service that demands operation at an essentially constant load for an indefinitely long time. This is the most common duty classification and accounts for approximately 90% of motor applications. (GE Motor Selection and Application Guide) (Reference 10.22)

3.2.2 INSULATION RESISTANCE TEST (MEGGERING)

A test for measuring the electrical resistance between two conductors separated by an insulating material. (McGraw-Hill Dictionary of Scientific and Technical Terms 5th Edition) (Reference 10.23)

3.2.3 INTERMITTENT DUTY

A requirement of motor service that demands operation for alternate intervals of load and no-load, load and rest, or no-load and rest. (GE Motor Selection and Application Guide) (Reference 10.22)

3.2.4 POLARIZATION INDEX

The polarization index is a specialized application of the insulation resistance test.

The index is the ratio of insulation resistance at two different times after voltage application, usually the insulation resistance at 10 minutes to the insulation resistance at 1 minute. (NFPA 70B 18-9.2.3) (Reference 10.4)

NEMA National Electrical Manufactures Association
NFPA National Fire Protection Association
O&M Operations and Maintenance
PI Polarization Index Test
PP&PE Personal Property and Programmatic Equipment
PPE Personal Protective Equipment
RP&IE Real Property and Installed Equipment
SEM Systems, Engineering and Maintenance
SSC Structures, Systems, and Components
UC University of California
VOM Voltage/Ohmeter

4.0 RESPONSIBILITIES

4.1 FACILITY MANAGER

4.1.1 Responsible for operations and maintenance of institutional or Real Property and Installed Equipment (RP&IE), in accordance with the requirements of this document.

4.1.2 Responsible for operations and maintenance of those Personal Property and Programmatic Equipment (PP&PE) systems and equipment addressed by this document that may be assigned to the FM in accordance with the FMU-specific Facility/Tenant Agreement.

4.1.3 Responsible for system performance analysis and subsequent replacement or refurbishment of RP&IE and assigned PP&PE based on sound Life Cycle Analysis techniques and system-specific performance requirements.

4.2 FWO-SYSTEMS ENGINEERING AND MAINTENANCE (SEM)

4.2.1 Responsible for the technical content of this Criterion and assessing the proper implementation across the Laboratory. FWO-SEM should also provide technical assistance in support for implementation of this Criterion.

4.3 GROUP LEADER

4.3.1 Responsible for implementing operational and maintenance surveillance programs including the preparation and maintenance of required procedures and documentation for PP&PE under their jurisdiction that is covered by this Criterion.

5.0 PRECAUTIONS AND LIMITATIONS

5.1 PRECAUTIONS

This section is not intended to identify all applicable precautions necessary for implementation of this Criterion (e.g., lockout/tagout, confined space entry, PPE, etc.).

It is intended only to assist the user in the identification of hazards/precautions that may not be immediately obvious.

5.1.1 Personnel must be aware of a potential for electric motors with an automatic reset protector that has the potential of automatically restarting the motor. This could endanger personnel or equipment. These auto-start features can be located on the starter itself, through programmable logic controllers or variable frequency drives.

Such applications should use a manual reset protector or an identification placard to caution personnel. Note: Lockout/Tagout procedures must always be utilized when working on or around electric motors.

5.1.2 While re-lubricating motor bearings with grease and the drain plug is removed, under no circumstances should a mechanical probe be used while the motor is in operation.

Note: Lockout/Tagout procedures must always be utilized when working on or around electric motors.

5.1.3 Assure electric motor units are electrically grounded and electrical installation wiring and controls are used consistent with NEC and NFPA electrical code requirements. (NEC Article 430 and 250)

5.1.4 When approaching rotating electro-mechanical parts, such as couplings, pulleys, shafts, external fans, and unused shaft extensions, personnel should guard against accidental contact with hands, tools, or clothing. This is particularly important where the parts have surface irregularities such as keys, keyways, or setscrews.

5.1.5 Do not lift a motor and its driven load by the motor lifting hardware. Motor lifting hardware is adequate for lifting of the motor only.

5.2 LIMITATIONS

The intent of this Criterion is to identify the minimum generic requirements and recommendations for SSC operation and maintenance across the Laboratory. Each user is responsible for the identification and implementation of additional facility-specific requirements and recommendations.

Nuclear facilities and moderate to high-hazard non-nuclear facilities will typically have additional facility-specific requirements beyond those presented in this Criterion which are contained in their Technical Safety Requirements, Facility Safety Plans, Configuration Management Process, and the Unreviewed Safety Question Determination (USQD) process as applicable. Nuclear facilities must implement the requirements of DOE Order 4330.4B (or 10 CFR 830.340, Maintenance Management, when issued) as the minimum programmatic requirements for a maintenance program.

Additional requirements and recommendations for SSC operation and maintenance may be necessary to fully comply with the current DOE Order or CFR identified above. (Reference 10.5)

6.0 REQUIREMENTS

Minimum requirements that Criterion users must follow are specified in this section.

Requested variances to these requirements must be prepared and submitted to FWOSEM in accordance with LIR 301-00-02, “Variances and Exceptions to Laboratory Operations Requirements” (Reference 10.6) for review and approval. The implementation of these requirements will ensure that the subject SSC is maintained in a condition suitable and available for its intended use. The Criterion users are responsible for analysis of operational performance and SSC replacement or refurbishment based on this analysis. The requirements contained in this section are driven by LIRs, ARs and contractually agreed to codes, orders, and standards.

6.1 OPERATIONS REQUIREMENTS

6.1.1 Assure machine guarding for personnel safety on motor-driven equipment remains in place while in operation.

Basis: Based upon Occupational Safety and Health Administration regulation (Reference 10.19). Compliance with this standard is required per Appendix G of the UC Contract.

6.2 MAINTENANCE REQUIREMENTS

6.2.1 None.

7.0 RECOMMENDATIONS AND GOOD PRACTICES

The information provided in this section is recommended based on acceptable industry practices and should be implemented by each user based on his/her unique application and operating history of the subject systems/equipment.

7.1 OPERATIONS RECOMMENDATIONS

7.1.1 Motors are designed to operate at or below any maximum surface temperature stated on the nameplate. Failure to operate the motor properly can cause this maximum motor temperature to be exceeded and cause premature failure. If applied in a hazardous area, this excessive temperature may cause ignition of hazardous materials.

Operating motors at any of the following conditions may have the potential to cause nameplate temperatures to be exceeded:

- Motor load exceeding service factor value
- Ambient temperatures above nameplate value
- Voltages above or below nameplate value
- Unbalanced voltages
- Loss of proper ventilation
- Variable frequency operation
- Altitude above 3000 ft. Note: See 7.1.3
- Severe duty cycles – repeated starts. Note: See 7.1.2
- Motor stalls, motor reversing, or single phase operation

Basis: Recommendations provided by DOE Motor

Challenge Program. (Reference 10.7)

7.1.2 Avoid repeated unsuccessful restarts of electric motors that can create overheating of motor or external starting equipment. Generally, restarts in succession with electric motors will shorten motor life. Excessive restarts can be created both by automatic electric controls as well as manual operator actions. When additional starts are required, it is recommended that none be made until all conditions affecting operation have been thoroughly investigated and the apparatus examined for evidence of excessive heating. It should be recognized that the number of starts should be kept to a minimum.

Basis: Recommendation from National Electrical Manufactures Association - Number of Motor Starts. (Reference 10.15)

7.1.3 Los Alamos National Laboratory is located at an elevation of greater than 7000 ft.

The rating of standard motors assumes operation at sea level in a 40 deg. C ambient.

For purposes of standardization, it is considered that there is no difference in motor operating temperature between sea level and 3300 ft. The cooling effect of ventilating air is a function of its density. The atmospheric pressure and density at higher altitudes is reduced and the air cannot remove as much motor heat, causing the motor to run hotter. As a general guide, motor temperature rise increases 1% for every 330 ft. above 3300 ft. To keep motor heating within safe limits at altitudes above 3300 ft. the LANL Facility Engineering manual and the LANL Construction Specification Section 15170 provides provisions for de-rating motors for 7500-ft. altitude in accordance with NEMA MG1-12: 1% for every 300 ft. above 3300 ft. These specifications are requirements whenever a motor is being replaced or installed for the first time and should be utilized to provide proper cooling of motors for LANL applications.

Basis: Recommendation from National Electrical Manufactures Association and Engineering requirements of LANL Facility Engineering Manual.

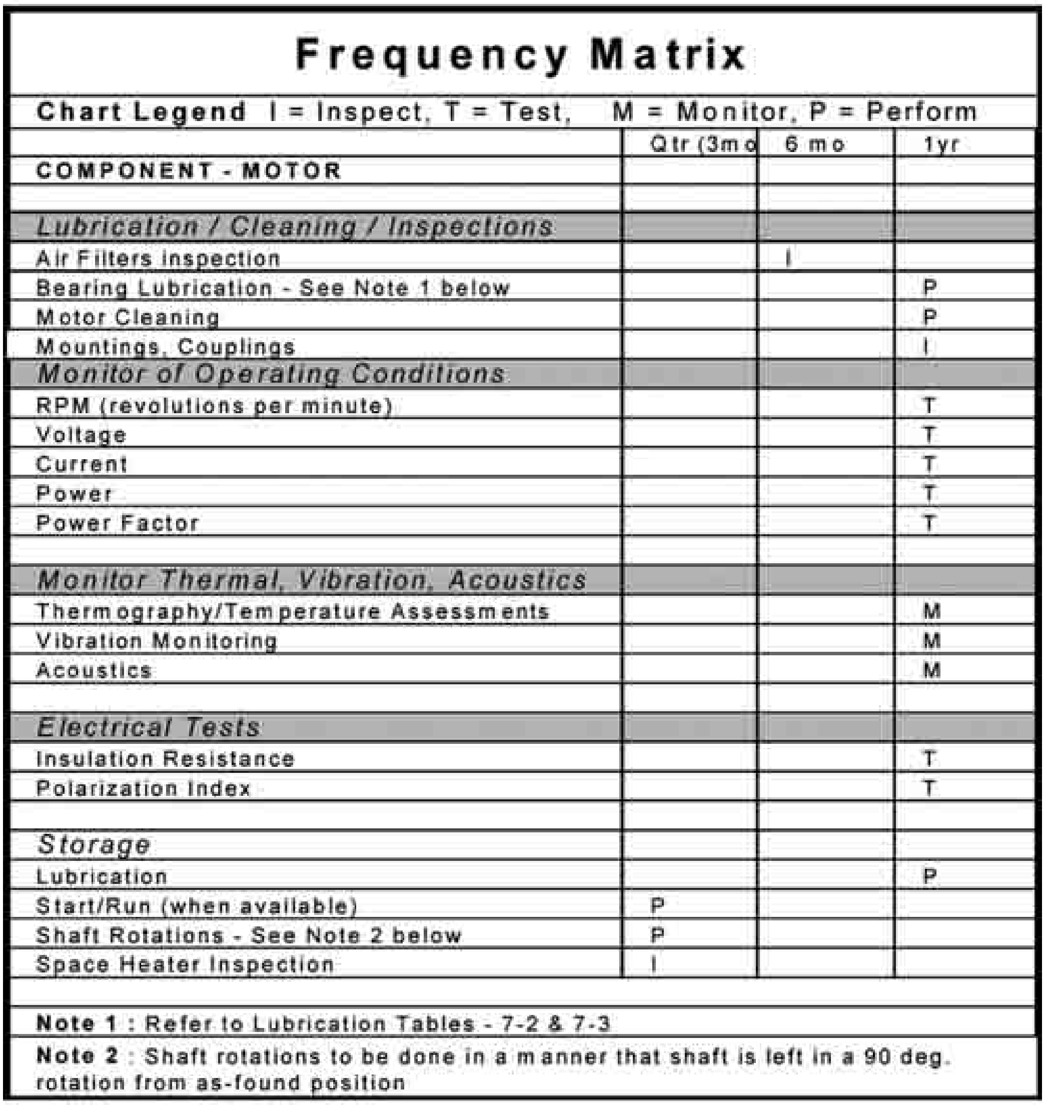
(References 10.15 and 10.21)

7.2 MAINTENANCE RECOMMENDATIONS

Careful and regular maintenance and inspections are required to detect and clear any faults as early as possible before major damage can develop. Only general inspection intervals for trouble-free operation can be recommended because of the widely differing operating conditions. The inspection intervals must therefore be matched to the prevailing circumstances (dirt, deposits, frequent starts, loading, temperature, etc.).

Special information provided by motor manufactures must also be followed.

Table 7.2-1 Frequency Matrix



Frequency Matrix

Chart Legend I = Inspect, T = Test, M = Monitor, P = Perform

	Qtr (3mo	6 mo	1yr
COMPONENT - MOTOR			
Lubrication / Cleaning / Inspections			
Air Filters inspection		I	
Bearing Lubrication - See Note 1 below			P
Motor Cleaning			P
Mountings, Couplings			I
Monitor of Operating Conditions			
RPM (revolutions per minute)			T
Voltage			T
Current			T
Power			T
Power Factor			T
Monitor Thermal, Vibration, Acoustics			
Thermography/Temperature Assessments			M
Vibration Monitoring			M
Acoustics			M
Electrical Tests			
Insulation Resistance			T
Polarization Index			T
Storage			
Lubrication			P
Start/Run (when available)	P		
Shaft Rotations - See Note 2 below	P		
Space Heater Inspection	I		

Note 1 : Refer to Lubrication Tables - 7-2 & 7-3

Note 2 : Shaft rotations to be done in a manner that shaft is left in a 90 deg. rotation from as-found position

Basis: Engineering judgement of standard industry practice and DOE Motor Challenge Program (Reference 10.7)

7.2.1 CLEANING

7.2.1.1 Maintain external and internal cleanliness of motors when deemed cost effective (based on size and cost of motor). Frequency will be based upon the conditions and atmosphere in which the motors operate.

Basis: Engineering judgement and Todd Litman, "Efficient Electric Motor Systems," The Fairmont Press, Inc., 1995, Lilburn, GA (Reference 10.8)

7.2.2 LUBRICATION

7.2.2.1 Lubricate motors based initially upon manufacturer's recommendations. Typical lubrication intervals vary from less than 3

LUBRICATION GUIDE	Motor Horsepower			
Type of Service	Up to 7.5	10 to 40	50 to 150	Over 150
Easy: infrequent operation (1 hr per day), valves, door opemers, portable floor sanders	10 yr.	7 yr.	4 yr.	1 yr.
Standard: 1- or 2-shift operation, machine tools, air-conditioning apparatus, conveyors, garage compressors, refrigeration apparatus, lauddry machinery, textile machinery, wood-working machines, water pumping	7 yr.	4 yr.	1.5 yr.	6 mo.
Severe: motors, fans, pumps, motor generator sets, running 24 hr per day, 365 days per year; coal and mining machinery; motors subject to severe vibration; steel-mill servic	4 yr.	1.5 yr.	9 mo.	3 mo.
Very Severe: dirty, vibrating applications, where end of shaft is hot (pumps and fans), high ambient	9 mo.	4 mo.	3 mo.	2 mo.

Table 7.2-2 Lubrication Frequency Guide
Basis: Data from vendor operation and maintenance manuals and "Incompatibility of Greases," NSK Techtalk Vol. 01, No. 02, April 1992; Technical Tip-Sheet of the NSK Corporation and "How to Get the Most From Your Electric Motors," Electric Apparatus Service Association, St. Louis, MO.; and NFPA 70B Table 19-3.7.3. (References 10.4,10.9, 10.10)

months for large motors subject to vibration, severe bearing loads, or high temperature continuous duty to ten years for smaller motors with intermittent duty. Motors used seasonally should be lubricated before the season of use. Small or fractional horsepower motors have sealed bearings that do not require re-lubrication. All larger motors require some form of lubrication.

Refer to Appendix A for an in-depth explanation on lubrication. It is important to note that the correct quantity of lubricant is vital to the proper operation of motor bearings.

Insufficient or excessive lubrication will result in failure. Reference the following lubrication frequency guide (see top).

7.2.3 MOUNTINGS AND COUPLINGS

7.2.3.1 Assure motor and load is firmly mounted to common structure or floor and motor-to-load couplings are firmly connected during maintenance performance.

Basis: Operational experience and recommendations provided by Richard L. Nailen, "Managing Motors," Barks Publications Inc., 1991, Chicago, IL. (Reference 10.11)

7.2.4 MONITORING OPERATING CONDITIONS

7.2.4.1 Test and monitor operating conditions at annual intervals as a minimum. Items to monitor are RPM, voltage, phase imbalance, current, power, and power factor.

Maintain historical records of this monitoring. As per Section 9.1 of this document.

Basis: Standard commercial operations field experience and DOE Motor Challenge Program. (Reference 10.7)

7.2.5 THERMAL, VIBRATION, AND ACOUSTIC MONITORING

7.2.5.1 Test electrical motors with high safety and risk levels on a routine basis for running temperature utilizing a contact thermometer at the middle of the motor housing and at the inboard and outboard bearing housings after the motor has come up to operating temperature and record (Thermography scans are acceptable as well). Test the same electrical motors for excessive vibration and acoustical noise that may alert experienced personnel to problems. Reference the following guide for guidance in motor vibration.

Resiliently Mounted Machines

RPM @ 60 Hz	Velocity in/s peak	Velocity mm/s peak
3600	0.15	3.6
1800	0.15	3.6
1200	0.15	3.6
900	0.12	3
720	0.09	2.3
600	0.08	2
Note: For machines with rigid mounting, multiply the limiting values by 0.8.		
(Ref. 10.15)		

Table 7.2-3 Vibration Limits – Solo Run Test
Basis: Operations and maintenance field experience show monitoring of critical motors closely on a routine basis has proven to be an excellent tool to prevent unsafe and/or critical conditions.

7.2.6 ELECTRICAL TESTS

7.2.6.1 Regular periodic electrical tests should be performed on motors and motor circuits.

These tests are usually performed on an annual basis to detect insulation problems.

The following insulation deterioration testing techniques are predictive maintenance so that appropriate measures can be taken on a planned, and not a crash-action basis.

· Insulation resistance testing, commonly called meggering or IR, is an important predictive electrical test that is useful when the data is properly recorded and trended.

· Polarization Index (PI) is a basic IR test that goes a step further with more definitive results. The test is maintained for 10 minutes. The ten-minute reading is divided into the 1-minute reading to yield a polarization index. The PI should be above 1 and remain relatively consistent over time; a PI of 2 is very good. A pronounced drop in PI is a potential indication of a loss of insulation integrity.

Basis: Recommendations by IEEE 43-1991 and International Electrical Testing Association. (Reference 10.12, 10.13, and 10.14)

7.2.6.2 Analyze testing results of predictive/preventative maintenance records after each scheduled maintenance. Utilize NFPA 70B for acceptance criteria of data recorded.

Basis: Recommendation of DOE Motor Challenge Program and NFPA-70B 14-1.2 1998 (Reference 10.4 and 10.7).

7.2.7 STORAGE AND TRANSPORT

7.2.7.1 Care and maintenance of spare motors is necessary to prevent premature damage leading to early failures. Lubricants can drain away or bleed, exposure to humidity can cause rust pits in bearing races and damage winding insulation, and exposures to vibration areas in a static condition will damage bearings. Several things are necessary to reduce the stress of storage. If the motors are connected, they should be started and run up to operating temperatures at a minimum quarterly basis. Motors in storage should have their shafts rotated manually on a quarterly basis to reposition the bearings and redistribute the lubricant. The shaft rotation must be done in such a way that from quarter period to quarter period, the shaft does not get rotated to its previous position but placed 90 degrees from previous as-found position. Utilizing a marking tape on the shaft and dating the time it was rotated is a good method. Some motors equipped with internal space heaters should be connected and energized to maintain a dry atmosphere within the motor.

Basis: DOE Motor Challenge Program. (Reference 10.7)

8.0 GUIDANCE

8.1 OPERATIONS GUIDANCE

8.1.1 Appropriate selection and maintenance frequency criteria for motors should be based upon two main categories in the following priority:

8.1.1.1 The graded approach category, that is a selective assignment of resources to the maintenance of motors based on their level of risk, mission impact, or criticality, and cost of replacement or repairs. Motors are assigned to one of four categories based on the potential impact of a worst case failure on public safety, worker safety, the environment, safeguards and security, and the programmatic function. The categories are identified as ML1, ML2, ML3, and ML4, with ML1 representing the highest level of importance and the most rigorous level of maintenance and ML4 representing the lowest level of importance and requiring less frequent maintenance activities. (Reference 10.3).

8.1.1.2 The maintain or replace approach category, that is a selective decision for each individual motor as to whether motor maintenance will be performed regularly or whether the motor will be allowed to operate until failure. The following factors to consider when making these selective decisions to maintain or replace are:

· Importance of having the motor back in service immediately

· Type and size of the motor (e.g., horsepower, efficiency rating)

· Application (speed/torque requirements), electrical operating costs and hours operated annually

· Simple payback analysis

· Cost and availability of repair service versus the cost of a new motor

· Age and repair history of the motor

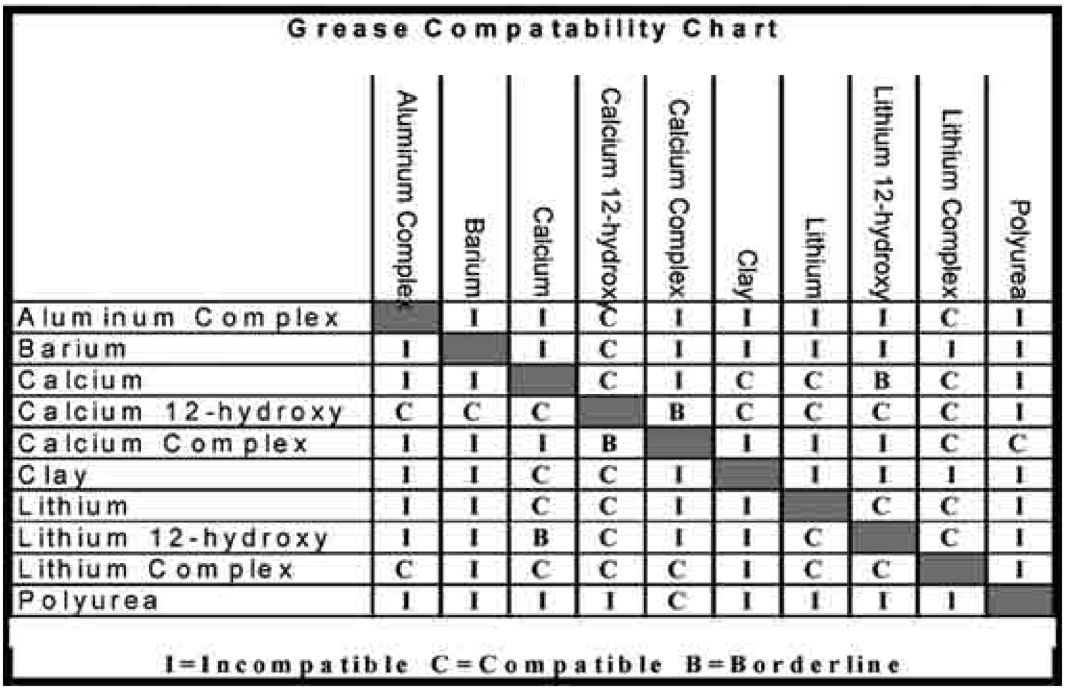
· Maintenance and capital budgets

Basis: Based upon data provided by Electrical Apparatus Service Association (EASA) Chuck Yung, Technical Support Specialist, St. Louis Missouri. (Reference 10.9)

8.2 MAINTENANCE GUIDANCE

8.2.1 Clean motors run cooler. Dirt and contaminants build up on fan-cooled motor inlet openings and fan blades

Table 8.2-1 Grease Compatibility Chart



Grease Compatability Chart

	Aluminum Complex	Barium	Calcium	Calcium 12-hydroxy	Calcium Complex	Clay	Lithium	Lithium 12-hydroxy	Lithium Complex	Polyurea
Aluminum Complex	▨	I	I	C	I	I	I	I	C	I
Barium	I	▨	I	C	I	I	I	I	I	I
Calcium	I	I	▨	C	I	C	C	B	C	I
Calcium 12-hydroxy	C	C	C	▨	B	C	C	C	C	I
Calcium Complex	I	I	I	B	▨	I	I	I	C	C
Clay	I	I	C	C	I	▨	I	I	I	I
Lithium	I	I	C	C	I	I	▨	C	C	I
Lithium 12-hydroxy	I	I	B	C	I	I	C	▨	C	I
Lithium Complex	C	I	C	C	C	I	C	C	▨	I
Polyurea	I	I	I	I	C	I	I	I	I	▨

I=Incompatible C=Compatible B=Borderline

Note: It is necessary to remove old lubricants from bearings that are not compatible with introduction of new type grease. (Reference 10.10) reducing flow of air and increasing motor operating temperature. Surface dirt can be removed by various means. The most common means are compressed air (max. 30 psi), vacuum cleaning, and direct wipe down with rags and brushes. Internal contamination is more difficult to remove. The most effective method is to prevent internal contamination. Larger motors can have filters placed at air intake areas to reduce contamination. (Reference 10.7)

8.2.2 With further analyses and well-kept records, different types of lubricant, and/or optimized lubricant intervals improve a lubrication program. Improper greasing techniques shorten bearing and motor life. The thorough cleaning of grease relief ports, grease fittings, and grease gun nozzles prior to lubrication is necessary to allow for proper lubrication flow and for preventing introduction of contaminants.

Maintaining cleanliness of lubricant and preventing introduction of contaminants into the lubricant is a very common problem. Utilizing cartridges rather than bulk lubricant can prevent some contamination problems. The free flow of grease is important to prevent damage to motor bearings. Grease guns are capable of producing high pressures that can literally drive seals and shields out of the bearing. Mixing of incompatible greases will cause bearing failures. Refer to Table 8.2-1. Adding too much grease or adding grease too frequently can force grease past bearing shields into the motor windings.

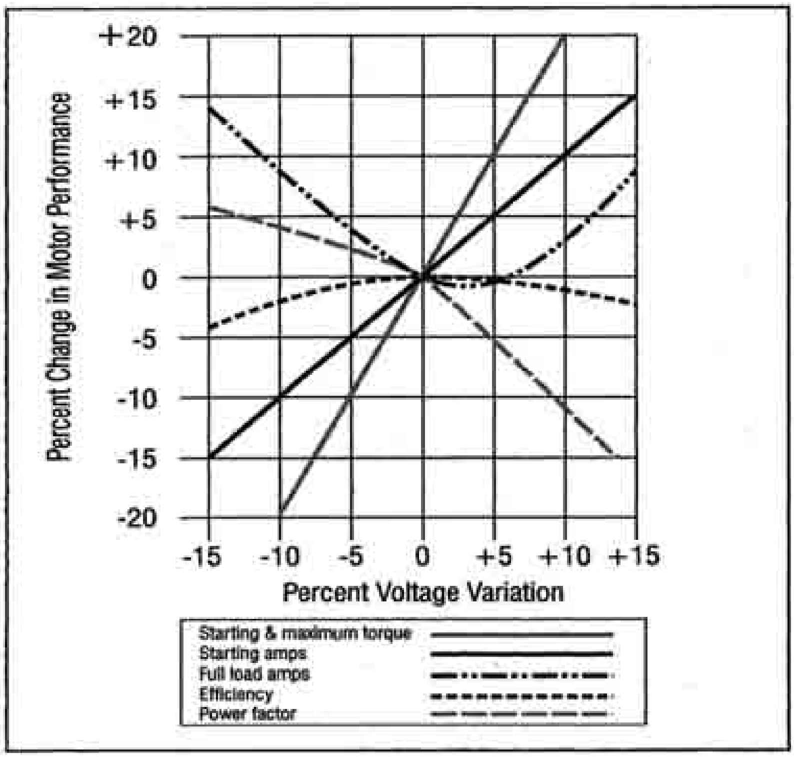


Figure 8.2-1 Effects of Voltage Variation on Induction Motor Performance Characteristics.

8.2.3 Motor and load must be rigidly bound to a common structure or floor. Failure to maintain solid mountings will lead to vibration problems that may lead to bearing failure. Coupling alignment is important to coupling and bearing life. (Reference 10.13)

8.2.4 Testing of operating speed should be performed utilizing a non-contact type tachometer for safety reasons. For belt-drive applications, it is important to measure the RPM of both the driver and the load to detect changes in slippage over time.

Voltage and current checks may be performed utilizing the standard clamp-on ammeter and VOM. It is important to note phase balance because unbalance can dramatically reduce motor efficiency and life. Check both voltage and current balance. A current imbalance over 2% is cause for immediate action. Significant changes in voltage are not likely to be caused by the motor, but affect the way a motor performs. Figure 8.2-1 shows how various load performance parameters tend to change with a departure from nameplate voltage. Power and power factor may be determined utilizing power factor meter or power meter. A maintenance procedure similar to JCNNM MOI 41-50-002, "Motor Circuit Evaluation" is acceptable provided it has been reviewed and approved by FWO-SEM. (Reference 10.9 and 10.18)

"Energy Management for Motor Driven Systems," US Department of Energy, Motor Challenge Program, June 1997, Rev. 1 (Reference 10.7)

8.2.5 NON ELECTRICAL TESTS

8.2.5.1 ALIGNMENT

8.2.5.1.1 All rotating equipment should be properly aligned when installed. The "eyeball" and straight edge, feeler gauges, and bubble gauges do not provide the precision required.

Rim and face and reverse dial methodology, or both, should be used. For high-speed equipment and precision work, laser-alignment technology is available. Laser alignment can provide the advantages of accuracy, speed and minimum chance for operator error. If the operating temperature of equipment changes significantly, thermal expansion should be considered.

8.2.5.2 THERMAL TESTING

8.2.5.2.1 Thermal testing is a good problem indicator. Thermography can also be utilized for thermal testing. It is not possible to measure surface temperature of a motor only once and infer its efficiency or general health. However, over time, increases in temperature that cannot be explained by other observed factors often signal problems.

A temperature increase away from the bearing housings is usually associated with something external to the motor that can harm the motor. Check for:

· Increases in loading,
· Obstructions to cooling air flow,
· Under-voltage,
· Development of a voltage unbalance condition,
· Line harmonics, and
· Recent multiples starts, or frequent jogging.

In variable speed drive motors, low speed without a dramatic torque reduction can cause overheating. Check with the drive and motor manufacturer regarding minimum safe speed for the torque loading. Some larger motors have temperature sensors built into the stator slots. This allows for effective monitoring, trending, and alarming of motor temperature limits. A maintenance procedure similar to JCNNM MOI 41-50-0010, "Infrared Thermography" is acceptable provided it has been reviewed and approved by FWO-SEM. (Reference 10.7 and 10.16)

8.2.5.3 VIBRATION

8.2.5.3.1 Vibration characteristics in motors can be used to indicate mechanical and electrical problems. Characteristics from the vibration summary spectrum (frequency vs. amplitude) and time waveform (time vs. amplitude) are used to identify motor problems such as: mass unbalance, bent shaft, coupling misalignment, broken/cracked rotor bars, stator eccentricity, loose electrical connections, rotor rub, mechanical looseness and bearing deterioration. Analysis and trending of these motor defects are performed in order to forecast equipment degradation so that "as-needed planned maintenance can be performed prior to equipment failure. A maintenance procedure similar to JCNNM MOI 41-40-002, "Equipment Vibration Data Collection/Analysis" is acceptable provided it has been reviewed and approved by FWO-SEM. (Reference 10.7 and 10.17)

8.2.5.4 ACOUSTICS

8.2.5.4.1 Acoustic monitoring can often alert experienced personnel to problems as well. The most common of these are bearing problems. Ultrasonic listening devices can sometimes detect pitting or arcing in bearings or the occurrence of arcing within windings. (Reference 10.7)

8.2.6 Establishing motor maintenance frequency is an iterative process. It is often necessary to prescribe somewhat frequent intervals at first (manufacture recommendations), then experiment with lengthening the intervals (refer to Section 7.2). Some activities can actually be harmful if performed too frequently (e.g. high voltage insulation testing and bearing greasing). If certain test results progress uniformly, you can establish a definite and often longer interval. Revise, but do not abandon the schedule. (Reference 10.7)

9.0 DOCUMENTATION

9.1 HISTORY

Data from inspection, testing, and maintenance should be recorded and controlled in equipment history files, e.g., CMMS. Computerizing the techniques proves to be the most efficient. The recorded equipment history information should be suitable to support maintenance activities, upgrade maintenance programs, optimize equipment performance, and improve equipment reliability. Utilize historical testing data to allow for trending analyses to be performed and identify needs for less or greater frequencies and weaknesses and strengths within the schedules chosen to be maintained.

9.2 DATA

Spreadsheets and database tools are useful for storing, manipulating, and analyzing data. Statistical software is often the best choice. DOE's Motor Challenge Program offers a special cost-free software package that is tailored specifically for motor performance and maintenance analyses (http://www.motor.doe.gov/). (Reference 10.7)

10.0 REFERENCES

The following references, and associated revisions, were used in the development of this document. Facility specific O&M procedures written to the requirements of this criterion should use the latest, LANL approved, revision of these documents.

10.1 LIR 230-05-01.0, Operation and Maintenance Manual.

10.2 DOE O 430.1A, Life Cycle Asset Management, Attachment 2, "Contractor Requirements Document," Paragraph 2, Sections A through C.

10.3 LIR 230-14-01.0, Laboratory Maintenance Management Program.

10.4 NFPA 70B-1998, Recommended Practice for Electrical Equipment Maintenance.

10.5 DOE O 4330.4B, Maintenance Management Program, Section 3.4.9.

10.6 LIR 301-00-02.3, Variances and Exceptions to Laboratory Operation Requirements.

10.7 "Energy Management for Motor Driven Systems," US Department of Energy, Motor Challenge Program, June 1997, Rev. 1.

10.8 "Efficient Electrical Motor Systems," Todd Litman, Fairmont Press, Inc. 1995.

10.9 "How to Get the Most From Your Electric Motors," Electrical Apparatus Service Association (EASA).

10.10 "NSK Tech Talk," Volume 1, No. 2, April 1992, Technical Tip Sheets of NSK Corporation.

10.11 "Managing Motors," Richard L. Nailen, Barks Publications, Inc. 1991.

10.12 NETA MTS-1997 International Electrical Testing Association, "Maintenance Testing Specifications for Electrical Power Distribution Equipment and Systems."

10.13 NETA ATS-1999 International Electrical Testing Association, "Acceptance Testing Specifications for Electrical Power Distribution Equipment and Systems."

10.14 IEEE Std 43-1991 The Institute of Electrical and Electronic Engineers, Inc. "Recommended Practice for Testing Insulation Resistance of Rotating Machinery."

10.15 NEMA MG1 – 1998 National Electrical Manufacturers Association "Motors and Generators" Sections 12.55, 12.13, and 7.8.1, Table 7-1.

10.16 JCNNM MOI 41-50-0010, "Infrared Thermography."

10.17 JCNNM MOI 41-40-0020, "Equipment Vibration Data Collection / Analysis."

10.18 JCNNM MOI 41-50-002, "Motor Circuit Evaluation."

10.19 OSHA 1910.212, Occupational Safety & Health Administration "General Requirements for all Machines," subpart title "Machinery and Machine Guarding."

10.20 Reliance Electric Motor Information Center,
http://www.reliance.com/prodserv/motgen/b5021.htm, "Reliance Proper Motor Lubrication White Paper – B-5021."

10.21 LANL Engineering Facility Manual, Chapter 7, Section 200, 248.5.5

10.22 GE Motor Selection and Application Guide

10.23 McGraw Hill Dictionary of Scientific and Technical Terms 5th Edition

11.0 APPENDIX

Appendix A: Reliance Proper Motor Lubrication White Paper – B-5021.

(See following page)

The service life of most motors is dependent on a little bit of good grease at the right times. This report discusses the pros and cons of different types of bearings, under-or-over-lubrication problems, and proper lubrication techniques.

Most motor failures are related to bearing failures. However, most bearing failures are not the result of bearing fatigue but improper lubrication. Bearing fatigue life calculations are commonly referred to as L-10 life (previously B-10). These calculations, expressed in thousands of hours of bearing life, give a good indication if a specific bearing can handle a specific load; but they cannot and should not be used to predict bearing life. Why? Because it all comes back to taking care of that bearing with good lubrication practice.

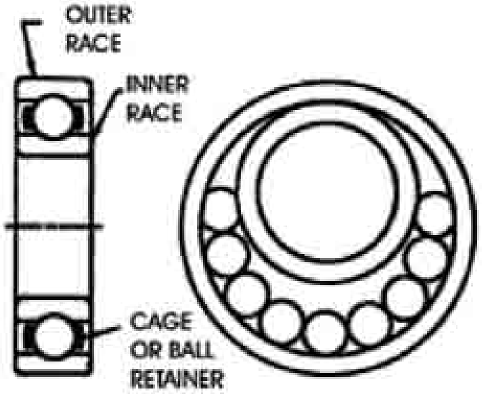
Before we can discuss good lubrication practices, we need to understand the basic types of bearings that motor manufacturers generally use, along with their advantages and disadvantages.

OPEN BEARING

Single Row, Deep Groove Ball Bearing: This is sometimes called a Conrad bearing and is listed by AFBMA (Anti-Friction Bearing Manufacturers Association) as Type BC (single row radial contact without filling slot).

The Conrad open bearing is assembled by eccentrically offsetting the thinner and outer races to allow the insertion of balls (see figure below). The Conrad type bearing therefore has uninterrupted raceways (no filling slot) which permits excellent bearing performance under light to moderate radial loads, relatively moderate thrust loads, or combined radial and thrust loads.

This bearing is also somewhat self-aligning and typically allows for a minor misalignment of ^{o}f without affecting the bearing operation and life.



Open Bearing

ADVANTAGES:

1. Open bearings (non-shielded) minimize friction allowing cooler bearing operation.

2. Not as susceptible to over-greasing because they have no shields to collapse.

3. Allows for complete and unrestricted grease relubrication.

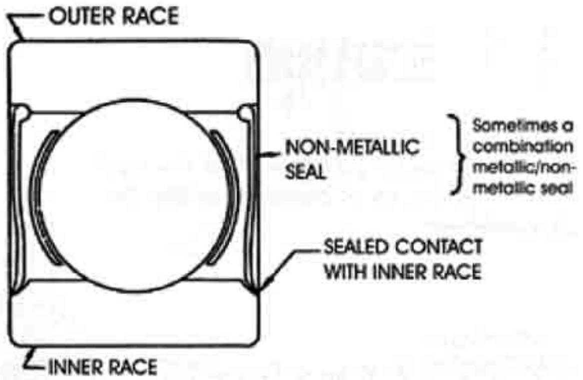
DISADVANTAGES:

1. The bearing system must be designed to protect the open bearing from contamination.

2. Grease must be restricted from migrating out of the bearing cavity.

SEALED BEARING

A "sealed" cartridge width bearing is a variation of the standard deep groove Conrad bearing. The construction of the raceway, cage, and ball assembly is the same; however, between the inner and outer rings are mechanical non-metallic seals. A "sealed" bearing cannot be relubricated.


OUTER RACE
NON-METALLIC SEAL
Sometimes a combination metallic/non-metallic seal
SEALED CONTACT WITH INNER RACE
INNER RACE

Sealed Bearing

ADVANTAGES:

1. Entry of contamination is greatly restricted.

2. No regular relubrication is necessary.

DISADVANTAGES:

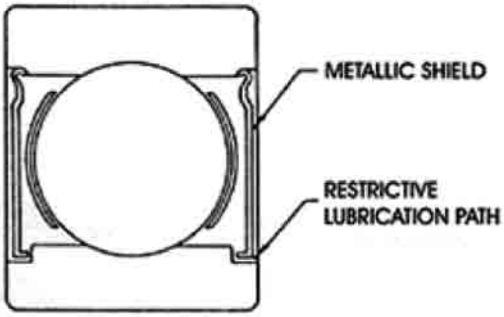
1. The bearing life is limited by the amount of lubrication packed between the seals of the bearing and the lubricant life.

2. The practicality of using sealed bearings is restricted due to the excessive heating on larger sizes.

3. Maintenance requires replacement of the bearing.

SHIELDED BEARING

A shielded bearing also is a variation of the Conrad bearing and is similar to the sealed-type bearing except that the shielded bearing has a metallic rather than a nonmetallic shield. The metal member is secured to the outer race with a close running clearance to the inner race. With care a shielded bearing can be relubricated. (A shielded bearing may be shielded on one side or both sides.)



Shielded Bearing

ADVANTAGES:

1. Retains the lubricant at the rolling elements regardless of the chamber fill.

2. Provides relubrication to the balls by the slinger feeding of inner race.

3. Restricts contamination from getting into the rolling elements at installation and during operation.

DISADVANTAGE:

1. Excessive pressure with no relief provided can force the shield against the cage or balls, eliminating regreasability or causing immediate failure.

LUBRICATION TECHNIQUES

If most motor failures are due to lubrication problems - how do they fail? First, it could be lack of lubrication for whatever reason. Second, it could be contamination of the bearing system. Third, believe it or not - too much grease. We all know that if you don't grease a motor, sooner or later it's going to fail. Or, if for some reason (such as heavy wash-down usage) you lose grease in the bearing, a failure is imminent. High motor and bearing temperatures also will tend to dry up the grease over time.

Contamination due to dirt and other foreign matter should also cause concern. Dirt and other hard particles such as metal and chips from abrasive wheels can get into the bearing raceways and be squeezed between the balls and raceway. This will cause roughness of the race and ball and will eventually cause failure. If the particles are a consistency of a very fine dust, they will act like a lapping compound and cause accelerated wear of the races and ball.

So like it or not, we are faced with regreasing most motors. It is important, when we do regrease, that the grease is clean and fresh; that the grease entry is also free of dirt and contamination; and most important, that the new grease is compatible with the existing grease.

OVER-GREASING

In many cases, over-greasing can be just as damaging as under-greasing. Heat is the biggest enemy a bearing has, and over-greasing causes the bearings to run at higher temperatures. When you combine over-greasing with other factors such as high bearing loading, you get excessive bearing heating and premature failure.

The other concern of over-greasing is that if the bearing is the shielded type, excessive pressure with no relief provided can force the shield against the cage or balls, thereby, eliminating regreasability or causing an immediate failure.

HOW MUCH IS ENOUGH?

An easy question without an easy answer. The best advice is to consult the manufacturer's instruction manual. Remember this rule of thumb: It is better to use a little grease more often than a lot of grease less often.

Relubrication frequency depends on environmental conditions. Under extreme conditions such as heavy shock, vibration, or dust, relubrication every one to three months is not uncommon. Under normal conditions relubrication every year or longer may be acceptable. Here again the manufacturer's recommendation and experience are the best guidelines. But nobody, including the motor manufacturer, knows the application and lubrication needs better than the people that work with the equipment every day.

Another tip is to regrease the motor while it's still warm. This will allow the existing dirty grease to flow freely and it will provide better relubrication. Also, remember to unplug grease drains (if provided) during regreasing. For safety reasons, always disconnect power before relubricating.

A little bit of common sense, a little bit of grease, and a good lubrication schedule will keep the industrial motors of today running a long, long time.

DESIGNING AN EMULATED GASOLINE/DIESEL TEST STAND DYNAMOMETER TO INCLUDE ENGINE FIRING TORQUE PULSES

B.T. Boulet, Applied Industrial Control Solutions LLC

INTRODUCTION:

Automotive industry Dynamometer applications that are designed to test drive-shaft components such as transmissions and/or differentials may use an electric motor in place of a gasoline/diesel engine to simulate the shaft torque dynamics of an engine based test stand. These test stands can also be designed to include pulses that emulate the drive-shaft stresses that result from individual piston firing torques. This paper describes the hardware and software that is required to perform this task.

DYNAMOMETER TEST STAND SYSTEM ARCHITECTURE OVERVIEW

The Engine-less Dynamometer system architecture shown in Figure 1 can be augmented to include the firing pulse torque generation algorithm and hardware. A complete description of the Engine-less Dynamometer can be found in “Designing a Dynamometer Test Stand with an Emulated Gasoline/Diesel Engine Power Source: A White Paper”. The augmented figure showing the INPUT stand Drive and Controllers is shown in Figure 2.

The Pulse Generator must inject the pulses at an analog input to the drive. The drive must also have a bandwidth that is higher than 4 pi times the maximum desired pulse frequency. It must also have the option of injecting the pulse torque reference directly into the analog side of the vector algorithm, NOT through an A/D converter and then summed with the sampled side of the vector algorithm.

The addition of the pulse generation algorithm, and the

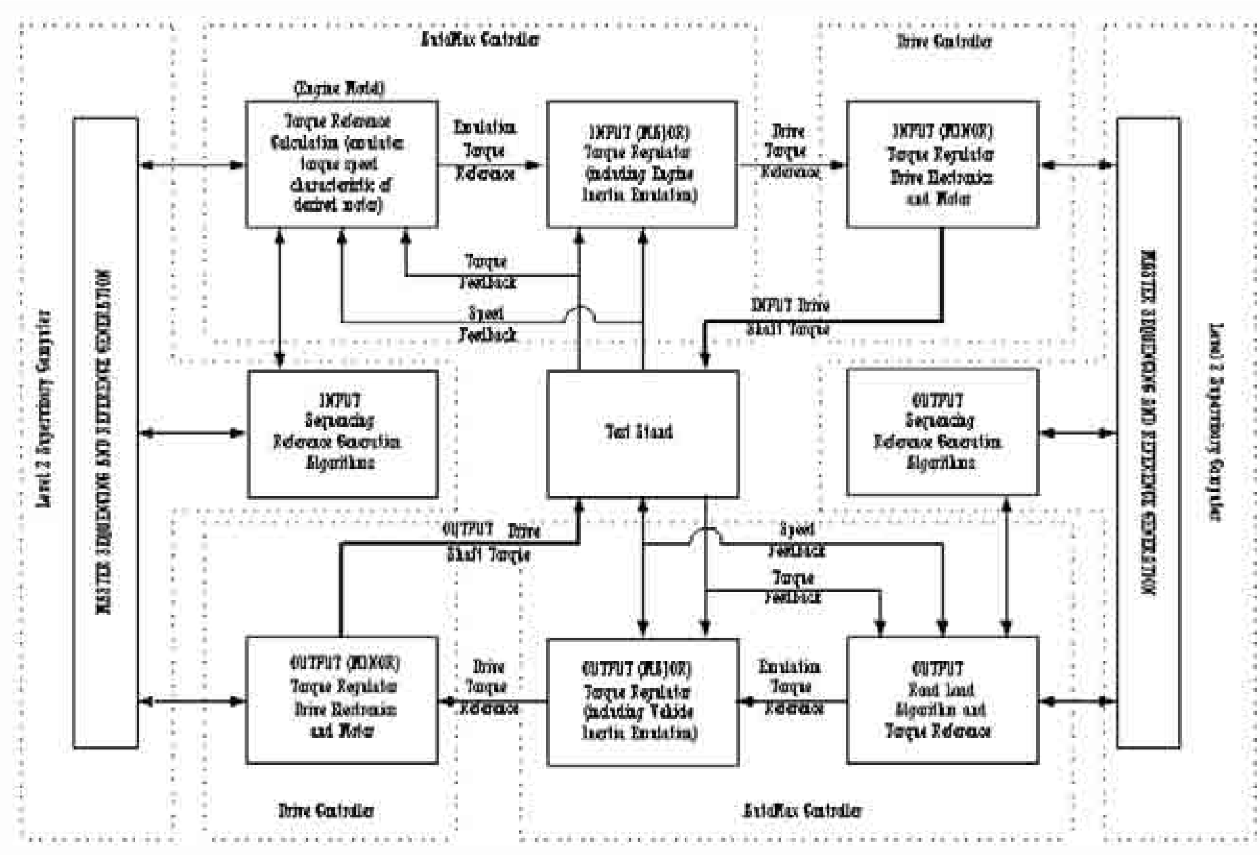

AutoMax Controller
Drive Controller
(Engine Model)
Torque Reference Calculation (emulates torque speed characteristic of desired motor)
Emulation Torque Reference
INPUT (MAJOR) Torque Regulator (including Engine Inertia Emulation)
Drive Torque Reference
INPUT (MINOR) Torque Regulator Drive Electronics and Motor
Torque Feedback
Speed Feedback
INPUT Drive Shaft Torque
Level 2 Supervisory Computer
MASTER SEQUENCING AND REFERENCE GENERATION
INPUT Sequencing Reference Generation Algorithms
Test Stand
OUTPUT Sequencing Reference Generation Algorithms
MASTER SEQUENCING AND REFERENCE GENERATION
Level 2 Supervisory Computer
OUTPUT Drive Shaft Torque
Speed Feedback
Torque Feedback
OUTPUT (MINOR) Torque Regulator Drive Electronics and Motor
Drive Torque Reference
OUTPUT (MAJOR) Torque Regulator (including Vehicle Inertia Emulation)
Emulation Torque Reference
OUTPUT Road Load Algorithm and Torque Reference
Drive Controller
AutoMax Controller

Figure 1. Engine-less Dynamometer System Architecture

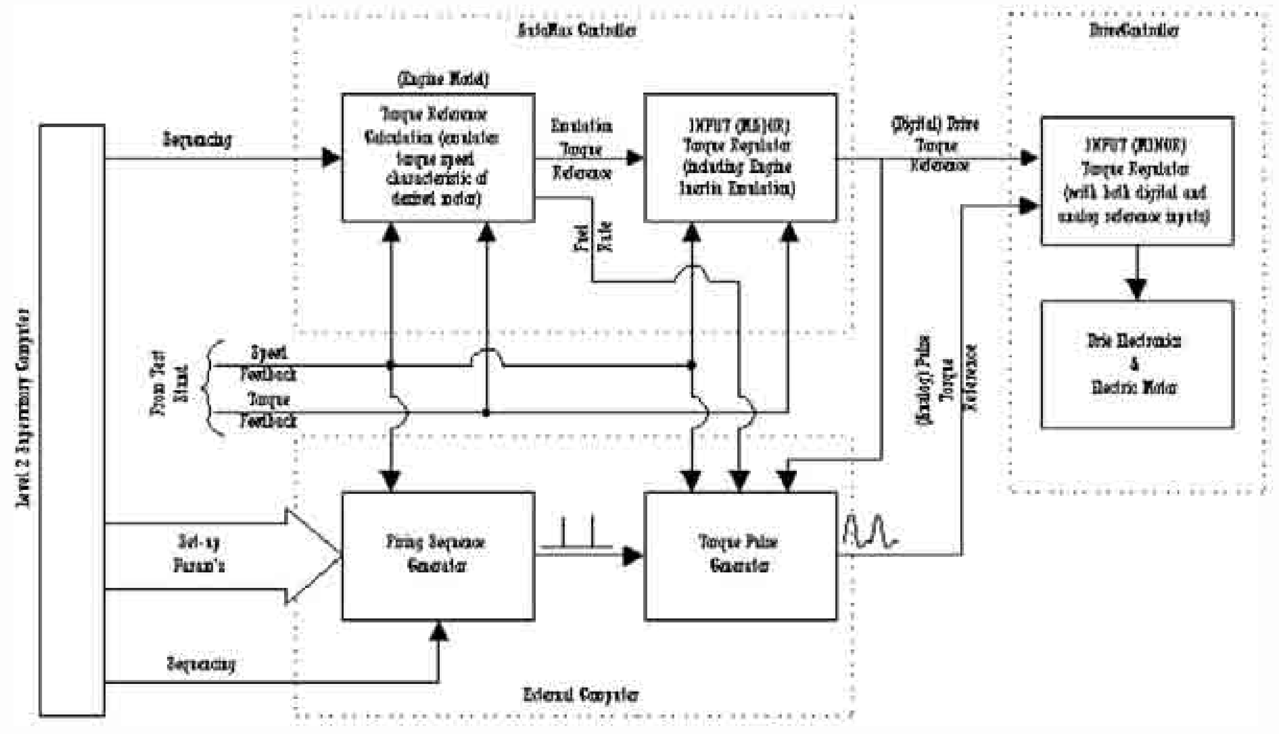

AutoMax Controller
(Engine Model)
Torque Reference Calculation (emulates torque speed characteristic of desired motor)
Sequencing
Emulation Torque Reference
INPUT (MAJOR) Torque Regulator (including Engine Inertia Emulation)
(Digital) Drive Torque Reference
DriveController
INPUT (MINOR) Torque Regulator (with both digital and analog reference inputs)
Drive Electronics & Electric Motor
Fuel Rate
Level 2 Supervisory Computer
From Test Stand
Speed Feedback
Torque Feedback
(Analog) Pulse Torque Reference
Set-up Param's
Firing Sequence Generator
Torque Pulse Generator
Sequencing
External Computer

Figure 2. Firing Pulse Generation

computer that is used to compute the pulse shape shown in Figure 2 enables the Test Stand to adequately simulate the torque pulses associated with the firing of cylinders in gasoline /diesel engines.

The efficacy of the pulse generation algorithm is dependent on the ratio of the computation performance of the computer producing the pulses and the amount of pulses per second. For example, an output sample rate that produces 2 computed torque pulse amplitudes per pulse will produce a completely inadequate representation of a torque pulse. On the other hand, an output sample rate that produces 100 computed torque pulse amplitudes per pulse will produce a very accurate representation. This relationship can be seen in Figure 3. As a rule of thumb, the minimum number of amplitude samples per pulse is 10.

Not shown in Figure 3 are additional problems associated with aliased signals. An output pulse sample rate that is 10 times higher than the maximum output pulse rate will significantly reduce these effects.

The firing sequence generator in Figure 2 computes the frequency of the pulse train, based on the speed feedback of the INPUT stand shaft and a set of engine set-up parameters.

$$f_{\mathrm{PULSE[Hz]}} = \frac{\omega_{FB[RPM]}}{60} \times \frac{n}{X}$$

where:

$\omega_{FB[RPM]}$ = Feedback [rpm] of the INPUT stand motor shaft.

n = number of cylinders to simulate

X = 1,2,3 or 4, depending on the engine type (i.e. V-8/6, Straight 4/6, 4/2 stroke)

The pulse shape generator calculates the amplitude of each sampled pulse output based on a predefined torque pulse shape, the fixed D/A sample rate, and the calculated pulse frequency.

PULSE SHAPE CONSIDERATIONS

The shape of the torque pulse that is used as the template in the pulse shape generator algorithm will vary depending on the engine cylinder size, the engine type, the instantaneous fuel rate, the firing frequency, and the output of the TORQUE MAJOR torque regulator.

Briefly, the pulse shape is constrained by the following:

- The normalized time average of the area under the computed pulse curve should be equal to the normalized time average of the output of the TORQUE MAJOR regulator.
- The height of the torque pulse is a non-linear function of the fuel-rate and the engine speed.
- The two above statements imply that the width of the pulse shape will vary depending on the output of the torque regulator, the instantaneous fuel rate, and the engine speed.

The first bullet indicates that the calculation of the pulses should be done at a considerably faster rate than the scan time of the INPUT MAJOR torque regulator. This is to ensure that the time average of the pulse generator is at least 10 times faster than the effective corner frequency of the INPUT MAJOR torque regulator (i.e. fSAMPLE RATE > 10/(p x TSCAN TIME))

The exact non-linear relationship between the height of the pulses, the instantaneous fuel rate, and the engine speed can either be determined heuristically (with measurements for a given engine) or analytically. The analytical solution may prove to be very involved.

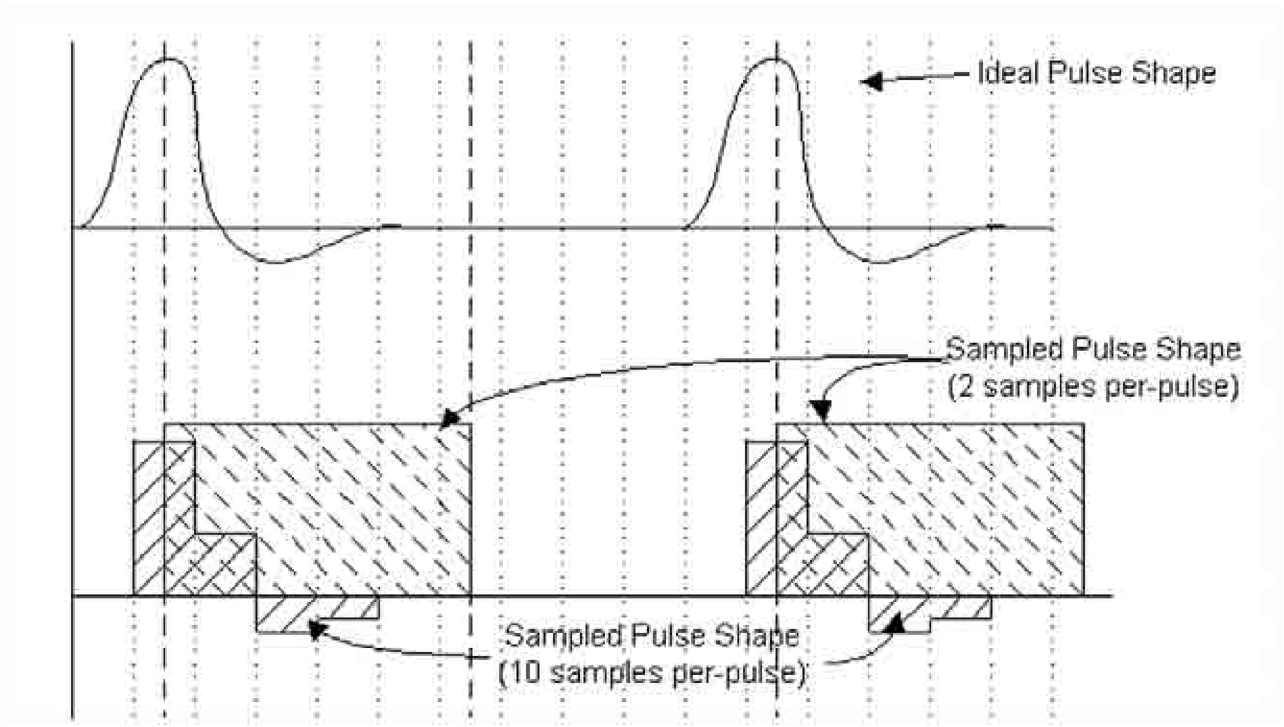


Figure 3. Output Sample Rate

A load sharing scheme may be used to split the torque reference from the INTPUT MAJOR torque regulator directly, and the output of the pulse generator algorithm. For example a 50/50 load sharing scheme will result in directly feeding 50% of the output of the INPUT MAJOR torque regulator to the INPUT MINOR torque loop, and dividing the output of the pulse generator by 50%. The ideal set-up would be realized when the direct feed from the INPUT MAJOR torque regulator is set to zero, and the entire torque reference is derived from the pulse generation algorithm.

HARDWARE AND SOFTWARE CONSIDERATIONS

Given that the minimum number of computed pulse amplitude samples per firing pulse is 10, the sample rate at which the output pulse computer must calculate the pulse amplitude must be:

$$f_{\mathrm{SAMPLERATE\,[Hz]}} \geq \frac{\omega_{MAX[RPM]}}{60} \times 10 \times \frac{n}{X}$$

Similarly, the corner frequency of the drive [rad/sec] must be greater than:

$$f_{\mathrm{DRIVE\,[r/s]}} \geq f_{\mathrm{SAMPLE\ RATE\,[Hz]}} \times 4\pi$$

The software must be capable of computing the amplitude of the output pulse at a rate greater than fSAMPLE RATE[Hz].

REFERENCING, SEQUENCING AND NOISE CONSIDERATIONS

Supervisory referencing and sequencing is handled in the Level 2 computer which communicates with the Automax regulators, the drives, and the pulse generation computer using standard communication protocols. Each application may require a custom communication package, and needs to be thoroughly investigated before proceeding with the design. Industry standard protocols are evolving at a brisk pace. Depending on the needs of the test set-up, the best communication package for each application must be identified prior to finalizing the design.

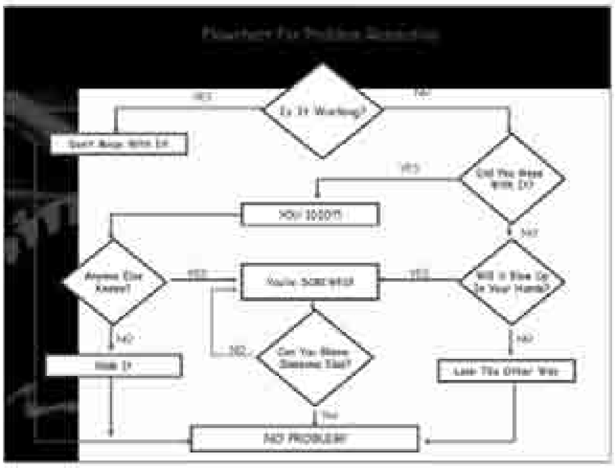
Considerable care must be given to the selection of the D/A converter used in the pulse output generator. It should have a linearity specification better than +/- 1%, and an s.n.r. better than 65 [db]. In addition, the D/A should be located as physically close as possible to the Analog input of the drive. This is to minimize noise corruption of the pulse signal. Care must also be taken to ensure that there are no ground loops in the system. This is because of the use of an analog signal as a critical reference signal in the control loop.

CONCLUSION:

An engine-less test stand may be configured to generate torque pulses that simulate the torque pulses that result from cylinders firing in a gasoline or diesel engine. The effectiveness of this approach is dependent on the use of a fast computational engine for the purpose of calculating the pulse shape.

ELECTRICAL SIGNATURE ANALYSIS

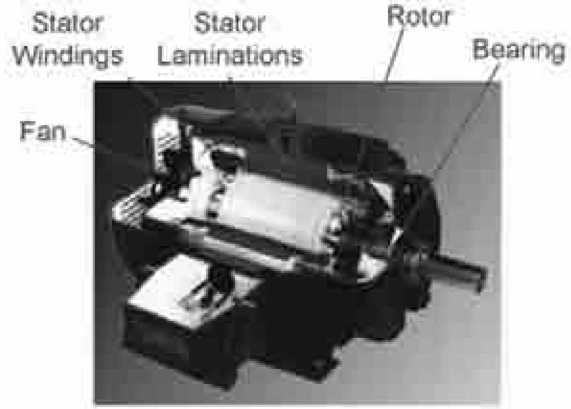
Dr. Howard Penrose, T-Solutions Inc.



Flow chart for problem resolution

Historically, the electrical reliability and maintenance professional was limited in ability to evaluate the condition of equipment. This resulted in challenges where the electrical professional was not as effective as his/her mechanical counterparts, where tools such as vibration analysis and similar technologies were developed. Repair by replacement had been the norm.

In recent history, this has changed with the application of motor circuit analysis and electrical signature analysis technologies. In this article, we will briefly discuss the application of ESA.



The Polyphase Induction Motor

This is a cutaway of a three-phase induction motor.

The fan is used to cool the motor.

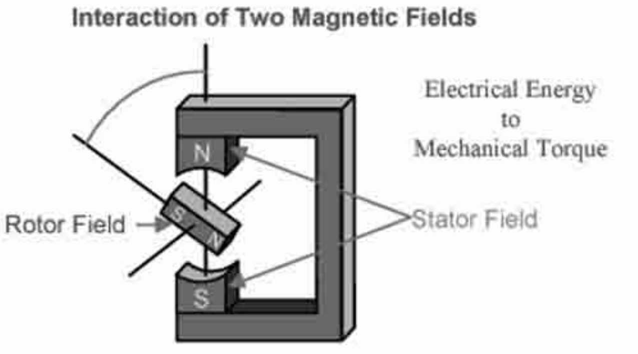
Bearings and end shields hold the rotor centered in the motor;

Stator laminations are designed to expel heat from the motor and reduce losses;

Stator windings are designed to be 120 degrees out of phase from each other and should be balanced.

Rotor windings are a series of bars that are shorted at each end of the rotor and have current induced into them during motor operation.

Between the stator and rotor windings is an air gap that must be maintained evenly about the stator. Uneven air gaps will cause low level vibration and will cause bearings to fail early.


Interaction of Two Magnetic Fields
Electrical Energy to Mechanical Torque
N
S
N
S
Rotor Field
Stator Field

Interaction of Rotor Field and Stator Field

A motor uses the magnetic properties of attraction and repulsion to turn a shaft.

In this simple diagram, wound coils around the stators create polarity.

As the current changes direction, polarity changes, causing the rotor to be continually attracted and repulsed as it moves.

Changes to impedance, inductance, and phase angle will affect the operation of the motor: its reliability, efficiency, and ability to develop torque.

In effect, an electric motor is an energy converter, converting electrical energy to mechanical torque.

Rotating Fields

As the three phases of electrical voltage separated by 120 electrical degrees enter the motor winding, which is separated by 120 electrical degrees, current and resulting magnetic fields are created. The sinusoidal waveform progressing from a positive value to a negative value generate a rotating field in the airgap of the stator.

Rotating Field and Rotor Cage

The rotating fields cut through the conductors, or rotor bars, of the rotor. The result is current flow and a second magnetic field. The motor acts, quite literally, as a transformer with a rotating secondary with the stator as the primary and rotor as the secondary.

The current flow in the rotor, with it at a standstill, is the same frequency as the supply voltage. For example, a 60 hertz supply provides a 60 Hz field in the rotor.

This generates a very high current, which is reflected through the stator windings as the four to eight times running current seen at the motor leads.

Rotor Cage

The magnet fields generated from the high current interact with the stator magnetic fields in the airgap between the stator and rotor. As a result, the rotor winding begins to follow the stator rotating field. The rotor can never catch up, however, as the rotating fields must always cut through the rotor bars.

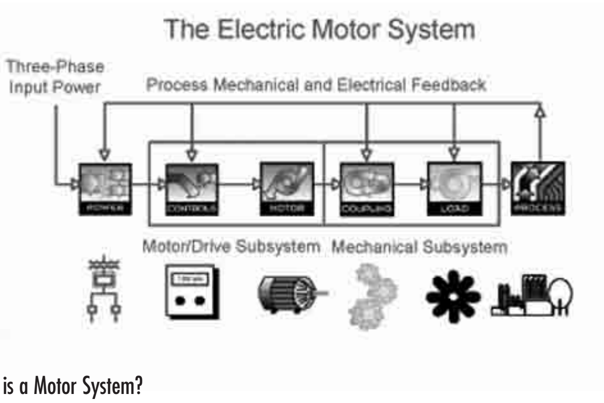
The relationship is such that, as the motor is loaded, the rotor slows down. This causes an increase in the rotor frequency and, as a result, the rotor current, which is again seen across the airgap and stator windings as an increase in current at the motor leads. From about 50% to 100% of load, the current can provide a reasonable estimate of loading.

Output Torque

Operating Motor

The rotor bars and shorting rings are connected to the rotor shaft, and, as a result, as the squirrel cage turns in the magnetic fields, torque is delivered through the shaft.

Together all of the components make up the electric motor.



What is a Motor System?

The motor system includes the power distribution system; the motor starting, control, and drive system; the motor; the mechanical coupling; the mechanical load; and the process.

The facility power distribution system includes components such as inplant wiring and transformers.

The starting, control, and drive system includes the motor starter and adjustable speed drives.

The motor itself – in this outline it is an induction motor.

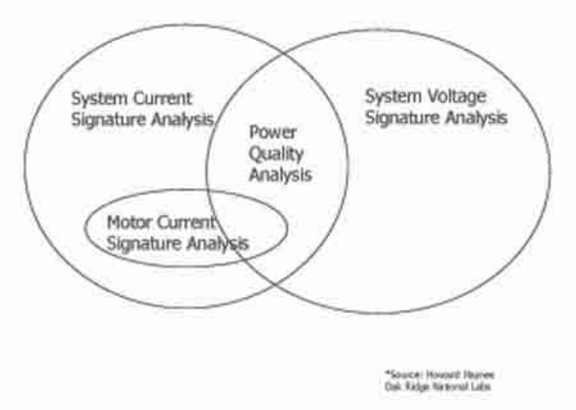
The mechanical coupling refers to components like v-belts and power transmission devices.

The mechanical load refers to the driven equipment, such as a pump, fan, compressor, or conveyor.

The process is what is being accomplished, such as water pumping, mixing, or aeration.

Most users look at motor systems from the component level and try to evaluate or troubleshoot.

The systems approach is a way of looking at the reliability of the entire system and the relationship and synergy of the components.


System Current Signature Analysis
System Voltage Signature Analysis
Power Quality Analysis
Motor Current Signature Analysis

*Source: Howard Haynes Oak Ridge National Labs

Electrical Signature Analysis

In this article, we will be focused on the voltage signature analysis of Electrical Signature Analysis. The system used is an Electrical Signature Analyzer.

Electrical signature analysis can be used to perform:

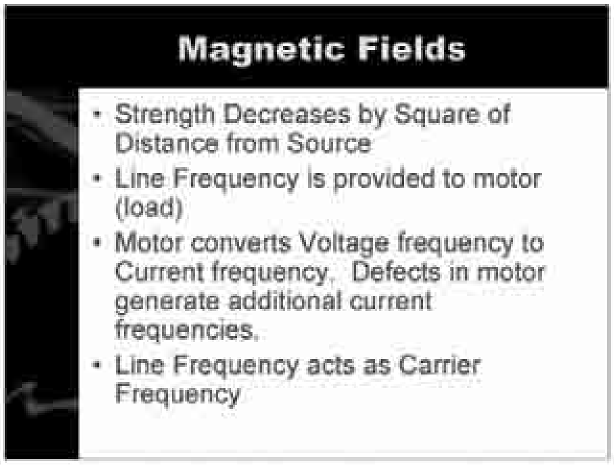
- System Current Signature Analysis is used for viewing systems other than motor current signature analysis including transformers and other loads.
- System Voltage Signature Analysis is used for viewing systems upstream of the point being tested including generators,

controls, VFDs and other supply loads

- Power Quality Analysis is used for performing advanced power analysis and data logging for power factor, voltage, current, demand, transients, surges, sags, swells and other power-related problems, including phase to neutral analysis.
- Motor Current Signature Analysis is used as a method for analyzing downstream of the point of test towards an electric motor for detecting rotor bar faults, later stage winding faults, and mechanical problems.

AIRGAP – CURRENT

The area that needs to be concentrated on, in order to understand electrical signature analysis, is the motor airgap and how it affects current.



Magnetic Fields

- Strength Decreases by Square of Distance from Source
- Line Frequency is provided to motor (load)
- Motor converts Voltage frequency to Current frequency. Defects in motor generate additional current frequencies.
- Line Frequency acts as Carrier Frequency

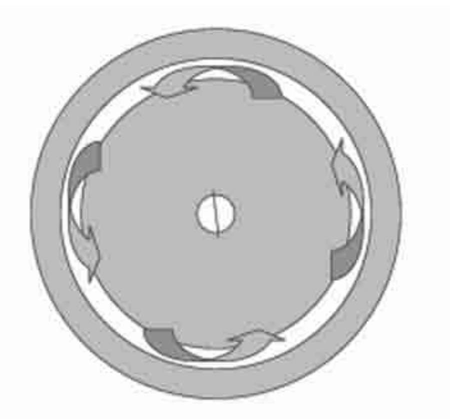
In order to understand how ESA works, it is important to know a few rules as to how magnetic fields, current and the supply frequency work to produce the signal we analyze.

First, the strength of the magnetic field decreases by the square of the distance from the source. This means that as the rotor bars recede or approach the stator magnetic fields, it will result in a change to the current in the stator.

A line frequency voltage is provided to the motor.

The motor converts the voltage frequency to the current frequency. Any defects in the motor or load generate additional frequencies within the current. In effect, the motor is a fault generator.

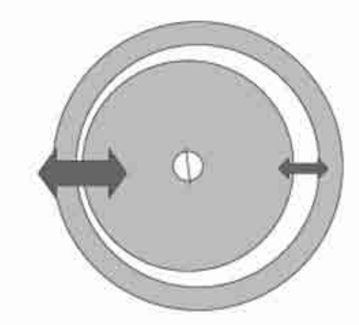
The line frequency acts as the carrier frequency which can be put through a fast fourier transform, or FFT, in order to pull the amplitude modulated frequencies out for analysis in an amplitude versus frequency spectra.



Good Airgap

In a perfect motor, the rotor is centered in the stator and all of the fields are even. If a perfect voltage sine wave is introduced, a perfect current sine wave results.

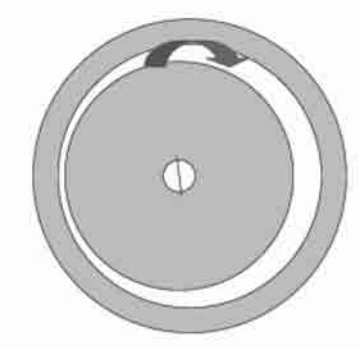
If there are any defect frequencies in the voltage sine wave, then those frequencies will appear in the current FFT, but at a smaller magnitude, due to the dampening effect through the motor and fields. In order to compare equivalent magnitudes, the results of both are shown in dB.



Static Eccentricity

When looking around the line frequency, it is common to 'demodulate' or remove the carrier frequency in order to look at the low frequency issues in the motor current.

In the case of static eccentricity, where the rotor is operating close to one side of the stator constantly, the magnitude of the interaction of the field on the side close to the stator is higher; and farther away lower. As the north and south fields occur close to the high and low magnitudes, the result is a series of frequency sidebands around the number of rotor bars times the running speed, also known as the rotor bar frequency.



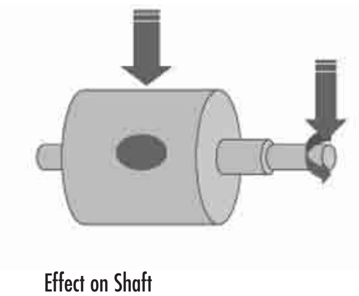
Dynamic Eccentricity

This type of signature usually shows as one and three times line frequency around the rotor bar frequency.

In the case of dynamic eccentricity, the rotor moves within the field at the running speed of the motor. This results in a frequency that is similar to static eccentricity, but with running speed frequencies around the line frequency sidebands.

All rotor and load related faults result in some form of rotor eccentricity with the movement of the rotor towards and away from the stator causing changes to the current waveform.

The degree of movement within the airgap causes a change in the magnitude of the dB signature sidebands. Because we are dealing with magnetic fields, there is normally not a peak at the calculated frequency, only at the sidebands, unless there is a significant fault.



Effect on Shaft

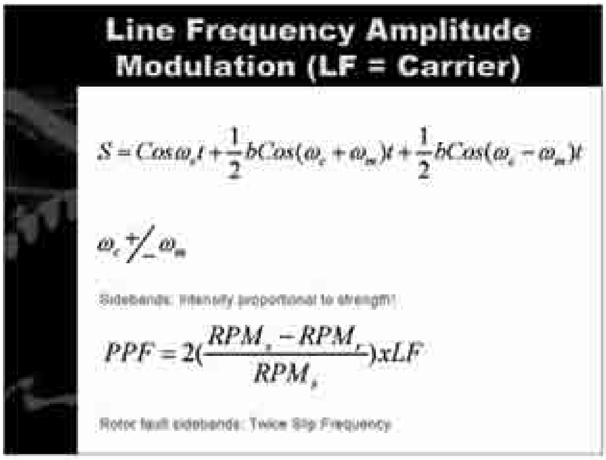
The shaft and rotor in the motor is not truly rigid. It moves.

One cause of movement is unbalance which puts a force on the rotor and resulting movement in the airgap.

Another cause is outside forces on the shaft, such as misalignment, belt tensioning, etc.

Torque on the output shaft will also cause the rotor to flex within the airgap, usually causing a raised noise floor around the line frequency or other frequencies.

Hot spots in the rotor will cause the rotor to bend causing dynamic eccentricity.



Line Frequency Amplitude Modulation (LF = Carrier)

$$S = Cos\omega_c t + \frac{1}{2}bCos(\omega_c + \omega_m)t + \frac{1}{2}bCos(\omega_c - \omega_m)t$$

$$\omega_c \,{}^{+}\!/_{-}\, \omega_m$$

Sidebands: Intensity proportional to strength!

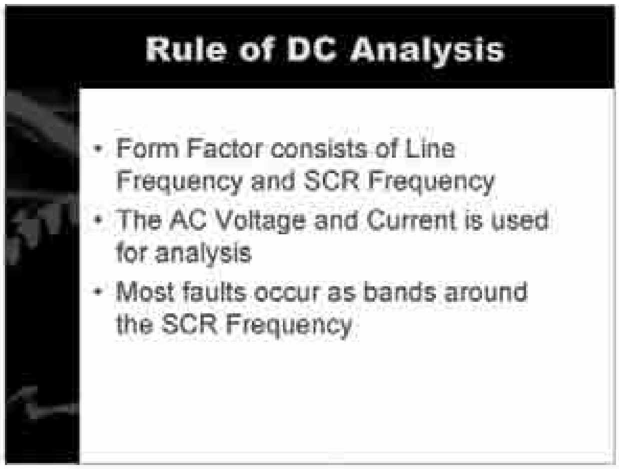
$$PPF = 2(\frac{RPM_s - RPM_r}{RPM_s})xLF$$

Rotor fault sidebands: Twice Slip Frequency

In a quick overview, the modulated carrier frequency is the line frequency. As a result, higher frequency faults will end up as multiples of the rotor bars and running speed for rotating problems and stator slots and running speed for stator problems.

In almost all cases, there will be sidebands of the line frequency as it is the carrier frequency. The amplitude of these sidebands is relative to the magnitude of the fault.

Rotor bar faults, one of the strengths of ESA, show as sidebands of twice slip frequency around the line frequency current.



Rule of DC Analysis

- Form Factor consists of Line Frequency and SCR Frequency
- The AC Voltage and Current is used for analysis
- Most faults occur as bands around the SCR Frequency

Believe it or not, it is not a significant leap from AC testing to DC testing using ESA.

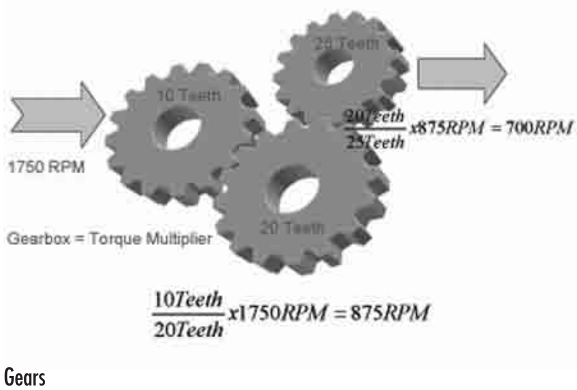
ESA uses sinusoidal voltage and current as the carrier. In the case of DC motors, when the sine wave passes through the DC drive, a small set of frequencies known as the form factor, which consist of the line frequency and the number of SCRs times the line frequency, result. These values are normally very low, in a good DC circuit.

Most faults occur in low frequency, or less than 120 Hz, and sidebands around the SCR frequency.

PERFORMING AN ANALYSIS

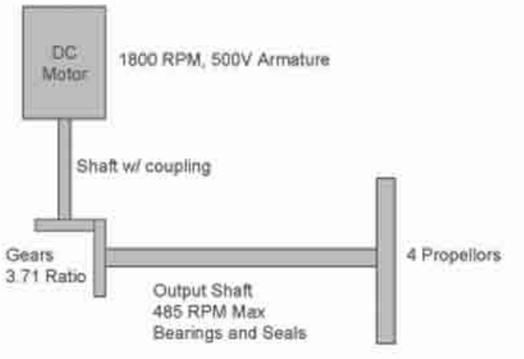
Knowing this, we will run through a short analysis of a DC system utilizing an RCM-Based approach.

As the system we will be analyzing includes gears, we will quickly discuss gear ratios.


20 Teeth
10 Teeth
$\frac{20Teeth}{25Teeth}x875RPM = 700RPM$
1750 RPM
Gearbox = Torque Multiplier
20 Teeth
$\frac{10Teeth}{20Teeth}x1750RPM = 875RPM$

Gears

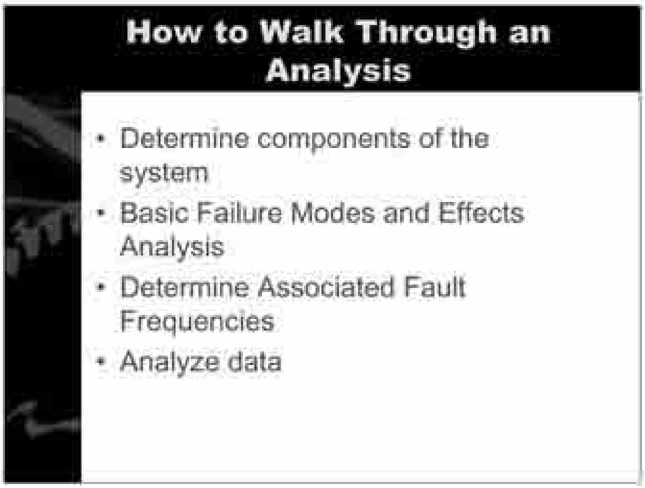
In a system that has a series of gears which include a 10 tooth gear, 20 tooth gear and 25 tooth gear, the intitial RPM is 1750, the reduced mid-speed is 875 RPM and the output speed is 700 RPM. The related frequencies are these speeds divided by 60 Hz.



Example

The system under review consists of a DC drive, a DC motor, a shaft with a coupling, a right angle gear with a 3.71 gear ratio, an output shaft that has bearings and mechanical seals and a four blade propellor on the output.

The max speed is 1800 RPM on the DC motor and 485 RPM on the output shaft.

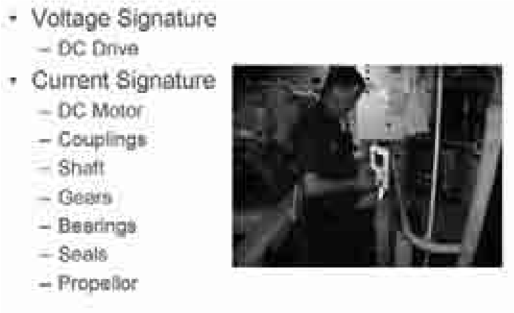


How to Walk Through an Analysis

- Determine components of the system
- Basic Failure Modes and Effects Analysis
- Determine Associated Fault Frequencies
- Analyze data

The way that I have successfully walked through most analysis on systems includes four basic steps:

1. Determine the components of the system
2. Determine the basic failure modes and effects of the system
3. Determine the associated fault frequencies of the most common faults
4. Analyze the data and FFTs



- Voltage Signature
  - DC Drive
- Current Signature
  - DC Motor
  - Couplings
  - Shaft
  - Gears
  - Bearings
  - Seals
  - Propellor

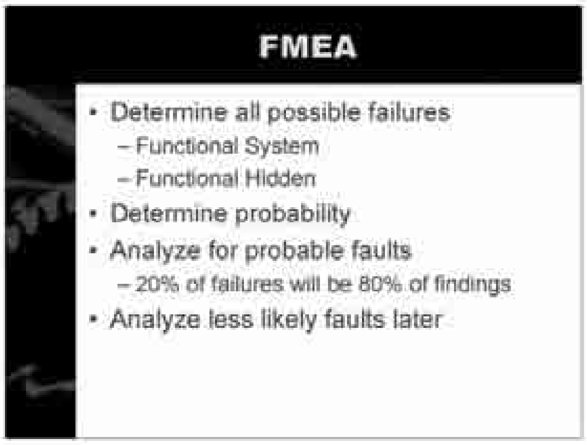
Components of a System

When reviewing the system, the components are as follows:

Voltage signature issues identify problems in the DC drive.

In Current, the following components are reviewed:

- The DC motor
- Couplings
- Shaft
- Gears
- Bearings
- Seals
- Propeller



FMEA

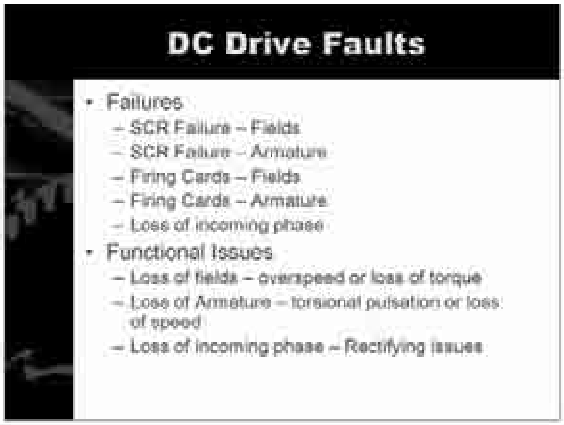
- Determine all possible failures
  - Functional System
  - Functional Hidden
- Determine probability
- Analyze for probable faults
  - 20% of failures will be 80% of findings
- Analyze less likely faults later

In the Failure Modes and Effects Analysis, the following is performed:

- Determine all possible failures, both obvious and hidden
- Determine the probability
- Understand that 20% of the potential faults will be 80% of the findings
- Analyze less likely faults if the primary faults do not show, in the instance of troubleshooting.

With the DC drive, the possible faults include:

- SCR Failure for either the fields or armature



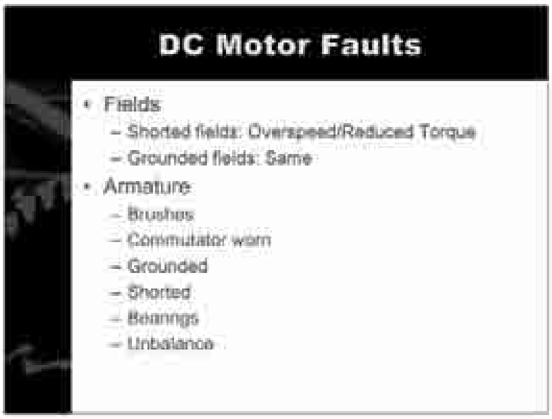
DC Drive Faults

- Failures
  - SCR Failure – Fields
  - SCR Failure – Armature
  - Firing Cards – Fields
  - Firing Cards – Armature
  - Loss of incoming phase
- Functional Issues
  - Loss of fields – overspeed or loss of torque
  - Loss of Armature – torsional pulsation or loss of speed
  - Loss of incoming phase – Rectifying issues

- Firing cards for the fields or armature
- The loss of an incoming phase

The functional issues show as:

- Overspeed or loss of torque due to a loss of the fields
- Torsional pulsation or loss of speed due to armature issues
- The loss of an incoming phase results in rectifying issues



DC Motor Faults

- Fields
  - Shorted fields: Overspeed/Reduced Torque
  - Grounded fields: Same
- Armature
  - Brushes
  - Commutator worn
  - Grounded
  - Shorted
  - Bearings
  - Unbalance

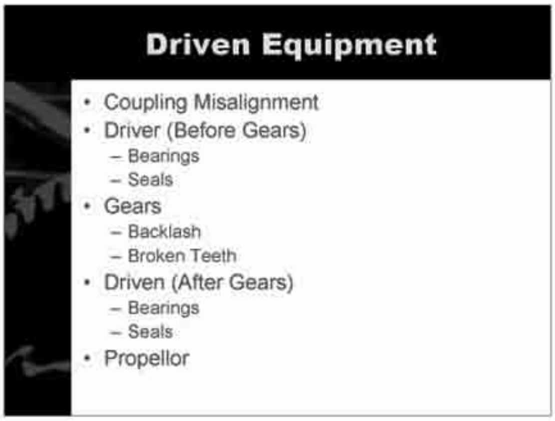
DC motor faults include:

In the fields:

- Shorted fields which result in overspeed or reduced torque
- Grounded fields will end with the same

In the armature:

- Brushes, commutator wear, grounding, shorted coils, failing bearings or unbalance.

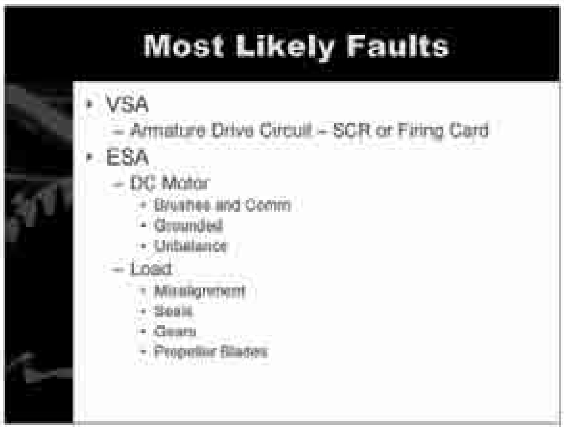


Driven Equipment

- Coupling Misalignment
- Driver (Before Gears)
  - Bearings
  - Seals
- Gears
  - Backlash
  - Broken Teeth
- Driven (After Gears)
  - Bearings
  - Seals
- Propellor

In the driven equipment, the following issues may result:

- Coupling misalignment
- Bearings and seals of the driven shaft before the gears
- Gear backlash or broken or cracked gear teeth
- Bearings and seals of the output shaft
- Propeller blade or cavitation problems



Most Likely Faults

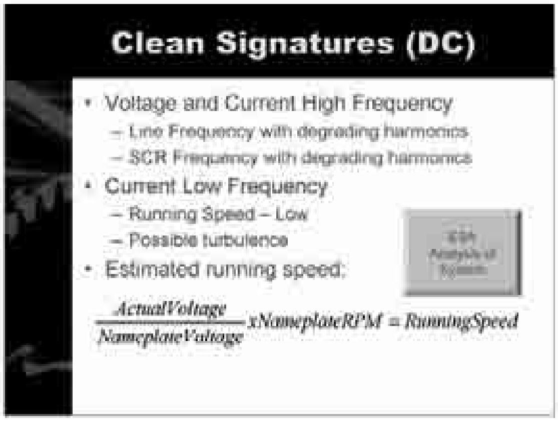
- VSA
  - Armature Drive Circuit – SCR or Firing Card
- ESA
  - DC Motor
    - Brushes and Comm
    - Grounded
    - Unbalance
  - Load
    - Misalignment
    - Seals
    - Gears
    - Propeller Blades

Based on the history of this type of system, voltage signature analysis will be used to evaluate the armature drive circuit to detect SCR or firing card problems.

Current signature analysis will be used to view conditions of the DC motor and load:

• In the DC motor, we will look for brush and commutator faults, grounded conditions and armature unbalance

• In the driven load, we will look for misalignment, seals, gears and propeller blade wear or damage.



Clean Signatures (DC)

- Voltage and Current High Frequency
  - Line Frequency with degrading harmonics
  - SCR Frequency with degrading harmonics
- Current Low Frequency
  - Running Speed – Low
  - Possible turbulence
- Estimated running speed:

$$\frac{ActualVoltage}{NameplateVoltage} xNameplateRPM = RunningSpeed$$

In voltage and current high frequency FFTs, there should be line frequency peaks with degrading harmonics and there should be SCR frequency peaks with degrading harmonics.

In low frequency current, there should be a low running speed peak and possible turbulence identified as a raised noise floor.

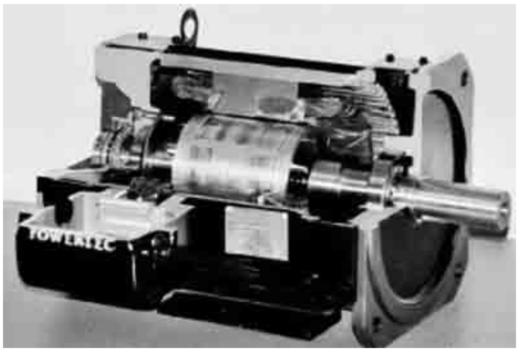
The estimated running speed can be calculated by dividing the actual armature voltage by the nameplate voltage. The result is multiplied by the nameplate RPM.

GETTING TORQUE-TO-INERTIA RIGHT

Ed Lee, General Manager, Powertec Industrial Motors Inc.

Crankshafts in running internal-combustion engines pulsate as well as rotate. This pulsation creates both primary and harmonic torsional stress on crankshaft-driven equipment such as superchargers, pumps, alternators, counterbalancers, and shafts. These components must undergo testing during design and production to check performance and quality. But on-engine component testing is expensive, time consuming, and often impractical. Hydraulic systems and offbalance rigs can simulate engine dynamics. But the equipment is difficult to use, expensive, and needs lots of maintenance.

Electric motors would be ideal for such testing. But it is impossible for most electric motors to produce rotational speeds of 500 to 6,000 rpm (or higher), while simultaneously varying those speeds up to ±10% at rates to 100 Hz or more. The reason: the ratio of torque to inertia, which is a measure of motor response.



A 15-hp, E-182 frame brushless-dc motor from Powertec uses neodymium permanent magnets on the shaft and a conventional three-phase stator winding. An internal resolver provides commutation and speed feedback for the drive controller.

For example, consider a case where you modulate the rotation of a 1-lb-ft2 load inertia 5% above and below a target speed of 2,000 rpm at 100 Hz. Torque must be applied to repeatedly accelerate and decelerate the load inertia in the allotted time. Assuming uniform acceleration, torque is given by:

$$T = (I \times \text{rpm}) / (308 \times t)$$

where T = torque (lb-ft), I = inertia (lb-ft^2), and t = time (sec).

In this example, a 25-hp motor can develop the 65-lb-ft continuous torque needed for the job. But the rotor in such an AC induction motor has inertia four times that of the load. In other words, the motor will need 260 lb-ft of torque to overcome its own inertia at the 100-Hz cycle rate. This amount of continuous torque is not available from the motor.

Another way of looking at the problem is to solve the above equation for rpm/sec. A 25-hp motor, based on rated torque and inertia, and with no other inertia attached to the shaft, could accelerate at 20,020 rpm/sec. Of course, the part to be tested also has inertia. It is common engineering practice to match motor and load inertia, then the total torque is 130 lb-ft. A typical 50-hp NEMA-standard AC-induction vector motor can continuously deliver this amount of torque. But it has a rotor inertia of about 5.5 lb-ft2, significantly higher than the target 1 lb-ft2. In fact, AC-induction motors — regardless of horsepower and torque ratings — cannot respond quickly enough for the application.

Brushless-DC motors, on the other hand, can. The reason: they have significantly higher torque-to-inertia ratios than AC-induction or brush-DC motors. A brushless-DC motor sized 50 hp or larger in this case meets specs for both response time and continuous power.

But there is more to system performance than motor torque. The controller must control motor-shaft speed at the desired cycle rate. A rule of thumb says controllers need a velocity-loop bandwidth of at least five times — ideally 10 times — greater than the frequency of motor-shaft speed variation. In this case, for 100-Hz variation, the velocity-loop bandwidth should be at least 500 Hz. Similarly, current-loop bandwidth should be five times the velocity loop bandwidth for the controller to work properly, or 2.5 kHz in this application. Moreover, for adequate control of motor current, the pulse-width-modulation rate should be at least five times the current-loop bandwidth.

These values are considered minimums and assume that the load is well characterized and the control algorithm does a loop-ahead calculation on actual output based on an output model (smart controller). Naturally, the question may arise: If smart controllers help brushless DC motors accurately track control inputs, can they do the same for AC-induction motors? Yes and no. Smart controllers can make AC-induction motors respond faster to control inputs, but they can't adequately overcome high rotor inertia for them to work in this application.

Another measure of drive performance is the rate at which the drive updates analog inputs. Many drives take 1 msec or longer to update analog inputs, excessively long to meet the bandwidth needs in this case. Analog inputs are ±10-VDC control signals that direct the drive to move a motor in a specified way. The signals may come from a signal generator, a computer program, or from the drive itself if it is programmed internally. Position and velocity feedback typically comes from a digital encoder or resolver.

Analog-to-digital converters should have at least 12-bit resolution to accurately define analog inputs over a broad speed range. A sinusoidal velocity signal processed by an 8-bit converter, in contrast, would pass to the controller as a trapezoid or other distorted shape because the resolution is too coarse.

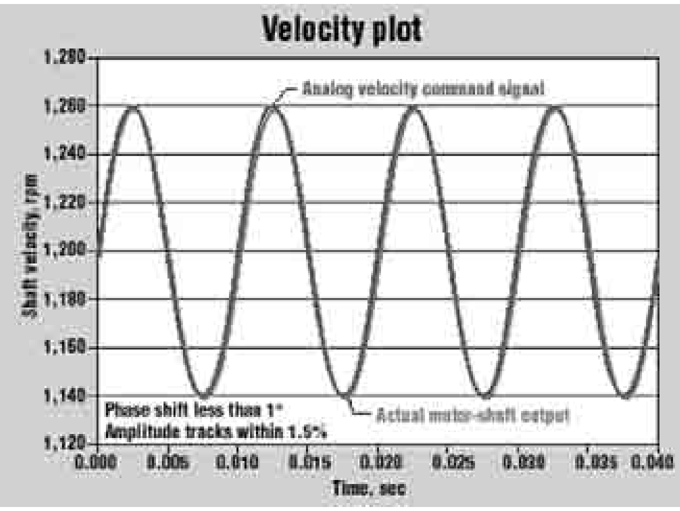
PUTTING MOTORS TO THE TEST

A torsional test machine inspects automotive superchargers during production at speeds to 6,000 rpm. Torsional-vibration tests take place at 2,000 rpm and vary speed ±5% at 60 Hz.

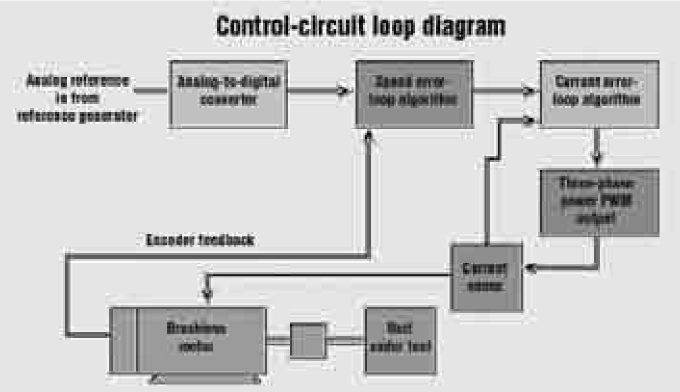
Total inertia is about to 1 lb-ft2. A brushless-DC motor rated at 60 hp at 6,000 rpm can do the job.

Another rig tests IC-engine counterbalancers. Such devices install on the crankshaft to counminimums teract primary and secondary torsional vibration from piston forces. This application varies rotation velocity ±5% about 1,200 rpm at 100 Hz. This application is impossible with motors having a torque-to-inertia ratio less than 60 lb-ft / lb-ft2.

Considering that the load itself has some inertia, motor inertia must be as small as possible, to a point. It is generally agreed, for stability reasons, that motor inertia should not be less than 20 to 25% of load inertia. Systems that match motor and load inertia consume the least amount of power and best track input signals (highest system bandwidth).



Plot of command and actual motorshaft velocity. The motor accurately follows an analog velocity command variation input. The controller accepts an analog input voltage and produces a smooth sinusoidal output with effectively no phase delay.


Control-circuit loop diagram
Analog reference in from reference generator
Analog-to-digital converter
Speed error-loop algorithm
Current error-loop algorithm
Three-phase power PWM output
Encoder feedback
Current sensor
Brushless motor
Unit under test

TYPICAL PERFORMANCE OF AC INDUCTION AND BRUSHLESS-DC MOTORS

Horsepower	Rated torque (lb-ft)	Frame size	Inertia (lb-ft2)	Frame size	Inertia (lb-ft2)
—— AC induction ——				—— brushless DC ——	
10	30	215T	1.1	E182T	0.3
15	45	256T	1.8	ES184T 0.4	
20	60	256T	2.3	E184T	0.5
25	75	284T	4.0	E213T	0.8
30	90	286T	4.7	E213T	0.8
40	120	324T	7.8	E215T	0.9
50	150	326T	9.7	E218T	1.1
60	180	364T	12.2	E254T	2.4
75	225	365T	15.3	E256T	2.9
100	300	405T	27.0	ES25T	3.8

GREASING ELECTRIC MOTORS - PART 1

Howard W. Penrose, Ph.D., Vice President, Electrical Reliability Group, T-Solutions, Inc.

INTRODUCTION

The lubrication of electric motors can be a critical maintenance practice for improved motor system reliability. Unfortunately, a significant amount of misinformation is provided within industry. For instance, those with a lack of knowledge of how motors and bearing work will often promote the 'purging' of motor grease, frequently. This practice puts undue stress on the motor, reducing its life and increasing the chance for both bearing failure and winding contamination.

Grease purging is the practice of forcing grease completely through the bearing housing and bearing until old grease is removed and new grease shows at the grease relief plug. While this practice is performed in highly contaminated environments, it provides many dangers to the reliability of the motor. There was many a time, as a motor repair journeyman, that I would disassemble or troubleshoot a motor winding or bearing failure in which the motor was full of grease. Some grease additives will react with winding insulation or will just provide a thermal blanket, reducing the life of the winding, when purged grease leaks through the bearing or bearing cap and onto the winding, even when you have the grease relief open.

Bearing lubrication, on the other hand, is the practice of adding enough grease to allow for the lubrication of the bearing friction surfaces and the eventual removal of contaminants from the grease housing. The purpose of this paper is to provide an overview and direction for the proper lubrication of bearings.

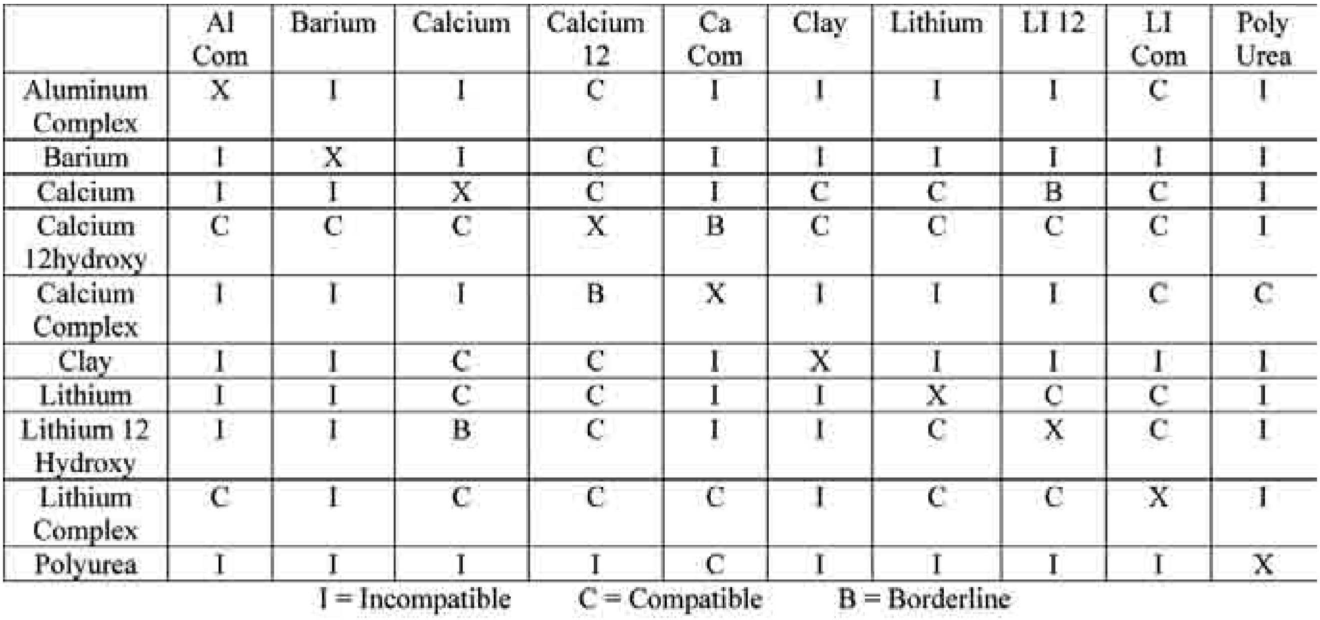
HOW A BEARING WORKS

The most common type of bearing is the AFBMA-7 C-3 rated bearing. C-3 relates to the internal clearances of the surfaces of the bearing. In most motor rated bearings, there is a clearance of between 3-5 mils (thousandths of an inch) in which lubrication flows to reduce friction and wear of the machined surfaces. The bearing, itself, consists of an inner race, an outer race, balls and a cage which evenly distributes the balls. Common bearings are designed to allow for a radial load with some limited axial loading. ALL BEARINGS ARE LUBRICATED WITH OIL.

Grease, itself, is an oil sponge. The base (spongy) part of the grease varies depending on the manufacturer, temperature, environment and user preference. The grease holds the oil in suspension and allows the oil to flow during operation. The oil compresses between the bearing balls, inner and outer races and the cage, reducing friction. Ball bearings have small, microscopically rough surfaces on the balls. These surfaces move the oil, holding it to the ball during operation.

When too much grease is added, the grease is compressed between the bearing surfaces, increasing pressure and resulting IN heat. Too little grease causes the surface friction to

Table 1: Grease Compatibility



	Al Com	Barium	Calcium	Calcium 12	Ca Com	Clay	Lithium	LI 12	LI Com	Poly Urea
Aluminum Complex	X	I	I	C	I	I	I	I	C	I
Barium	I	X	I	C	I	I	I	I	I	I
Calcium	I	I	X	C	I	C	C	B	C	I
Calcium 12hydroxy	C	C	C	X	B	C	C	C	C	I
Calcium Complex	I	I	I	B	X	I	I	I	C	C
Clay	I	I	C	C	I	X	I	I	I	I
Lithium	I	I	C	C	I	I	X	C	C	I
Lithium 12 Hydroxy	I	I	B	C	I	I	C	X	C	I
Lithium Complex	C	I	C	C	C	I	C	C	X	I
Polyurea	I	I	I	I	C	I	I	I	I	X

I = Incompatible C = Compatible B = Borderline increase, resulting IN heat. In any case, once bearing noise is audible, it has failed. Reducing noise by lubrication requires excessive grease, endangering the motor, and giving the technician the false security of extending the motor life when, in reality, additional damage is occurring to machined surfaces.

Bearings may also have shields or seals mounted on them. Bearing shields are metal fittings that have small clearances between the inner race of the bearing and contact the outer race on either side of the balls and cage. The small clearances near the inner race allow some oil and grease to move into the moving parts of the bearing, but prevent particles of large size from passing into the bearing potentially damaging machined surfaces. Sealed bearings have seal surfaces touching the inner race, while 'non-contact' sealed bearings have extremely close tolerances between the seal surface and the inner race preventing particles under several thousandths of an inch. Sealed, and some shielded, bearings are referred to as non-greaseable bearings.

PRECAUTIONS IN MOTOR GREASING

When greasing electric motors, there are a number of precautions that must be considered:

- When electric motors are manufactured, or repaired, grease fittings may be put in place on motors that are not grease able. Your supplier should be able to provide confirmation that the motor may be greased.
- Electric motors must be de-energized and locked/tagged out (LOTO) before greasing.
- There should be no paint on grease fittings.
- The average grease gun will introduce 1 ounce for every 23 strokes.
- Grease compatibility (See Table 1). The additives in some greases do not mix well and can cause the grease to solidify or liquefy.

GREASING PROCEDURE

Following is the standard procedure for greasing ball bearings:

1) Wipe grease from the pressure fitting, clean dirt, debris and paint around the grease relief plug. This prevents foreign objects from entering the grease cavity.

2) Remove the grease relief plug and insert a brush into the grease relief as possible. This will remove any hardened grease. Remove the brush and wipe off any grease.

3) Add grease per Table 2.

4) Allow the motor to operate for approximately 30 to 40 minutes before replacing the grease relief plug. This reduces the chance that bearing housing pressure will develop.

HOW OFTEN SHOULD BEARINGS BE GREASED?

Bearings should be lubricated at an average frequency as found in Table 3. Operational environment and type of grease may require more frequent lubrication.

CONCLUSION

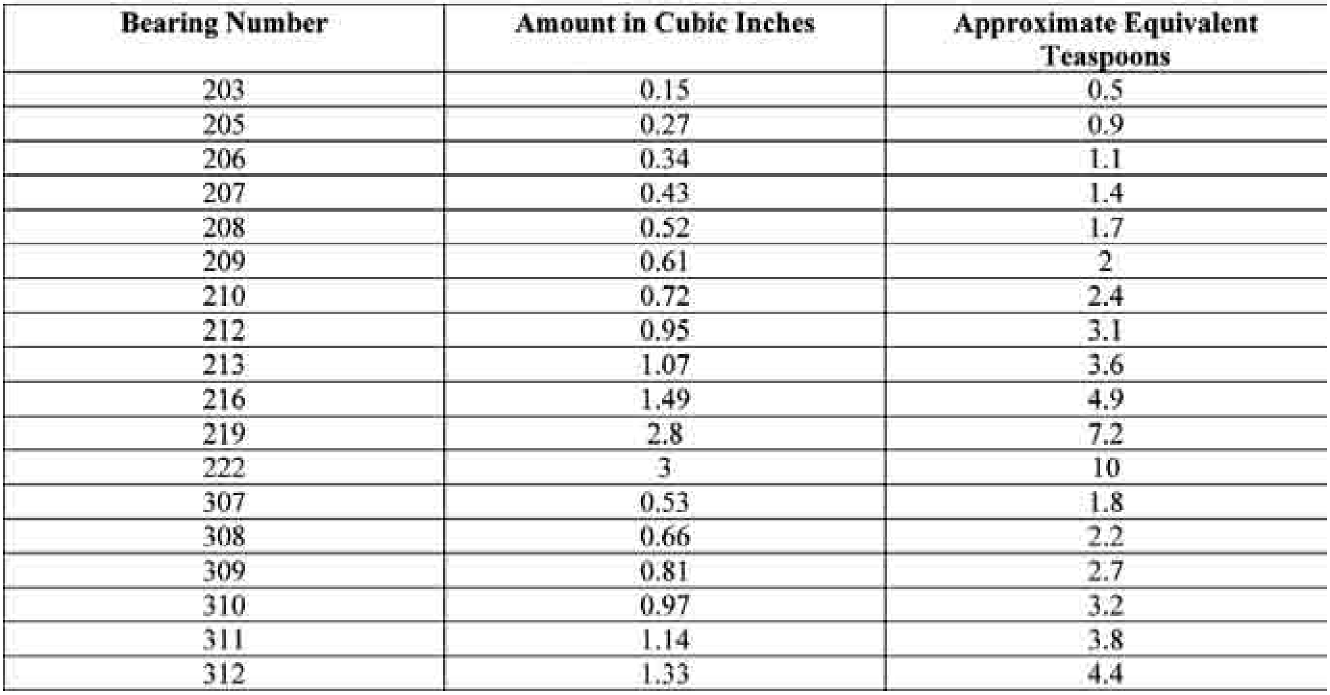
It is recommended that the type of grease used on each motor is recorded in order to avoid premature bearing failure. In many cases, you may be able to standardize the type of grease used in a majority of your motors. It is also good practice to let your motor repair center know the type of grease in case the standard grease used by the repair center conflicts with your standard grease.

BIBLIOGRAPHY

BPA, Energy Management for Motor-Driven Systems, Olympia, WA, WSU, 1997

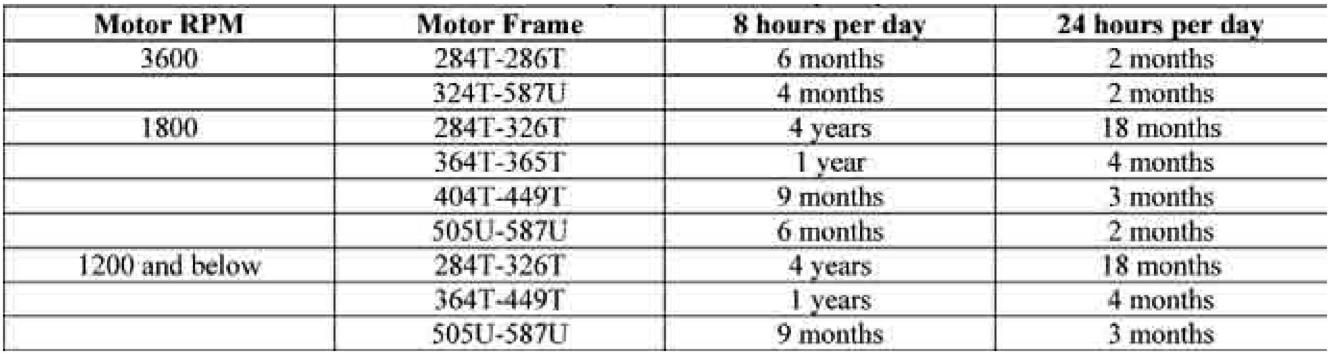
EASA, Mechanical Reference Handbook, 1993

Table 2: Amount of Grease to Use



Bearing Number	Amount in Cubic Inches	Approximate Equivalent Teaspoons
203	0.15	0.5
205	0.27	0.9
206	0.34	1.1
207	0.43	1.4
208	0.52	1.7
209	0.61	2
210	0.72	2.4
212	0.95	3.1
213	1.07	3.6
216	1.49	4.9
219	2.8	7.2
222	3	10
307	0.53	1.8
308	0.66	2.2
309	0.81	2.7
310	0.97	3.2
311	1.14	3.8
312	1.33	4.4

Table 3: Bearing Lubrication Frequency



Motor RPM	Motor Frame	8 hours per day	24 hours per day
3600	284T-286T	6 months	2 months
	324T-587U	4 months	2 months
1800	284T-326T	4 years	18 months
	364T-365T	1 year	4 months
	404T-449T	9 months	3 months
	505U-587U	6 months	2 months
1200 and below	284T-326T	4 years	18 months
	364T-449T	1 years	4 months
	505U-587U	9 months	3 months

GREASING ELECTRIC MOTORS, PART 2

Questions / Answers

QUESTION: HOW DO WE MEASURE THE AMOUNT OF GREASE RECOMMENDED IN THE FIRST PAPER?

Answer: Most lubrication, or grease, guns will provide information on the amount of grease they provide ‘per pump’. Therefore, many of the tables that I have used in the past have presented the information in ml or fluid oz. The key to remember is that the tables represent a guideline for lubrication as each motor manufacturer may have slightly different dimensions for the grease housing.

QUESTION: WHY MUST I DE-ENERGIZE MY MOTOR BEFORE LUBRICATION?

Answer: You might expect the answer to be strictly, ‘for safety’. However, there are several reasons. One, of course, is safety of personnel. A majority of electric motor installations require you to approach rotating components of the machinery or motor closely, providing a dangerous condition. In the USA, OSHA has specific policies about rotating machinery and guarding, which some may have to be bypassed in order to grease the motor. Is this a real concern? Yes, later in my field service career, I had a co-worker lose an arm to a large fan while he was working on an electric motor several feet away. I have also observed objects being snatched out of the hands of maintenance personnel while working on motors.

One way to get around this is to use a grease line from a safe location to the motor. If you do this, make sure to fill the line on initial installation so that you do not force air into the grease cavity and force out grease through any drain plugs or into the motor windings. You will also want to inspect the line to ensure that grease has not hardened within it, causing you to put bad grease into the grease housing. There is one other issue that would have to be addressed, as well. Is the machinery designed to be lubricated while it is operating? Some components and seals may act as grease pumps, moving grease into the motor and windings during greasing while the motor is operating. So, there is safety of the equipment to be considered. If you have addressed the ‘pumped grease’ issue with the manufacturer, grease lines are an option.

Most equipment manufacturers’ maintenance instructions that I have reviewed maintain the recommendation that motors are greased while the equipment is de-energized. The primary reason: Avoiding a lawsuit. And, with that, I maintain my original recommendations.

QUESTION: WOULDN’T USING A BRUSH TO REMOVE EXCESS GREASE CAUSE CONTAMINATION IN THE BEARING HOUSING?

Answer: Yes, it can, if not done properly or with a clean brush. The reason for using the brush is more important, and we will address that shortly. However, one of the reasons for using a clean brush is that any parts that come from the brush will probably be the strands from the brush which can be seen and removed. Also, a brush has a tendency to ‘pull’ grease out with the bristles, whereas a stick or other device will drive contaminated or dry grease into the bearing.

The more important reason for using the brush is simple. You must remove hardened grease from the drain plug, otherwise you may as well leave the grease plug in place. Grease will get into the motor and will cause a pressure buildup within the housing which may damage the bearing.

QUESTION: ARE THESE NEW ULTRASONIC AND VIBRATION-BASED GREASE GUNS AND ATTACHMENTS HARMFUL TO MY MOTOR? (AND VARIATIONS OF THIS QUESTION.)

Answer: Interesting, and dangerous question.

Each of these technologies relies upon lost energy, noise energy for ultrasonics and contact energy for vibration. When the energy loss in noise or vibration (contact) of an operating bearing increases, it means that the first stages of bearing failure are coming into play. Common practice has always been to add grease to an audibly noisy bearing to quiet it down, and these technologies are an extension of that train of thought. While a bearing is audibly noisy, it has effectively failed, one that is not yet in hearing is well on its way to failure with the energy coming from imperfections in the surfaces of the balls, cage and inner and outer rings. Adding grease until this noise is reduced means that the surfaces are being cushioned, which requires a substantial amount of the grease medium (the spongy part that holds the actual lubricant – oil) to be within the moving parts of the bearing. This causes a dampening effect of the contact energy, reducing the noise or contact vibration. As a result, you are extending the life of the bearing slightly but also causing the bearing to have to work harder by plowing through the grease (I am assuming that these devices stop you short of overly over greasing the bearings).

While I have not seen any reports from motor or bearing manufacturers showing the positive or negative results of these devices, myself, my only concern is that the greasing, by definition, must be done while the motor is operating and you must be able to get close to the rotating components to perform the greasing function. In this case, I must rely upon my previous information on greasing while equipment is operating.

IMPACT OF ELECTRIC MOTOR SYSTEM MAINTENANCE AND MANAGEMENT… ELECTRICAL MOTOR DIAGNOSTICS

Richard Borge, President, Performance Evaluation, Inc. and Howard W. Penrose

INTRODUCTION

The application of motor systems maintenance and management programs has the potential impact of saving industry an initial $26.5 Billion in electrical energy costs, while reducing greenhouse gas emissions by over 3,000 Mega-Tons per year. The individual impact on production availability is also significant, by reducing troubleshooting and evaluation time by over 50%, motor repair by over 30% and general motor-system related labor by up to 50%, following the application and sustainment of the program. In this article, we are going to cover three opportunities obtained through the application of the Electrical Motor Diagnostic component of an overall program.

OPPORTUNITY 1: APPLICATION OF MOTOR DIAGNOSTICS FOR PERIODIC TESTING

In a recent study, 1,054 motors were evaluated with MCA in a marine environment. The motor system owner's previous program involved the use of insulation to ground testing with a pass/fail limit of 1 MegOhm. The selected technology used in the study was an ALL-TEST IV PRO 2000 motor circuit analyzer which obtains data on resistance, impedance, inductance, phase angle, current/frequency response and insulation to ground testing.

During the period of testing, 35 machines were found to have insulation resistance values of '0' MegOhms. A total of 398 machines had a variety of potential faults identified as developing winding shorts, winding contamination, poor connections and/or a combination of faults (Figure 1).

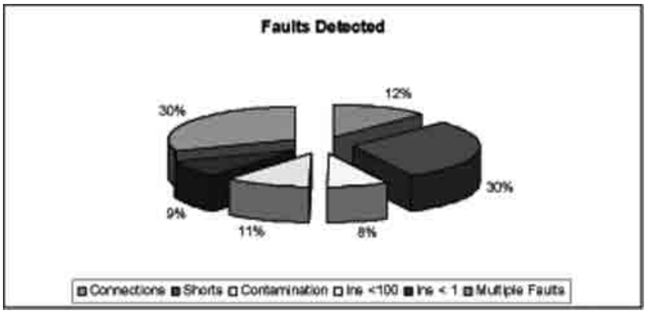


Figure 1: Faults and Types Detected

Of the 35 machines with low insulation resistance values, only one failed during the following eight months. This machine was also identified with developing winding faults. Of the remaining 363 machines, over 20% were identified as having failed over the next eight months. Note that additional machines may have also failed, however the data was limited based upon the accuracy of failure data entered into the associated CMMS software system.

A majority of the 1,054 machines were considered critical, with a number of them including fire pumps. Most of the identified motors were allowed to operate to failure. One of the significant issues identified in this study was that the application followed along with the expected 1 in 4 to 1 in 6 motors being identified with potential faults as identified in the 2003 "Motor Diagnostics and Motor Health Study".

OPPORTUNITY 2: APPLICATION OF MOTOR DIAGNOSTICS FOR PREDICTIVE MAINTENANCE

In 1996, a field service company initiated a motor diagnostics program utilizing an MCA device. The results were dramatic in that the number of annual motor repairs dropped by over 33% while production remained constant (Figure 2). The impact was an improvement in equipment availability and planned outage overhauls (the correct machines were removed for attention). There was also a direct reduction in emergency work orders by over 66%, which directly translated into a reduction in maintenance overtime costs allowing a higher rate of completed PMs.

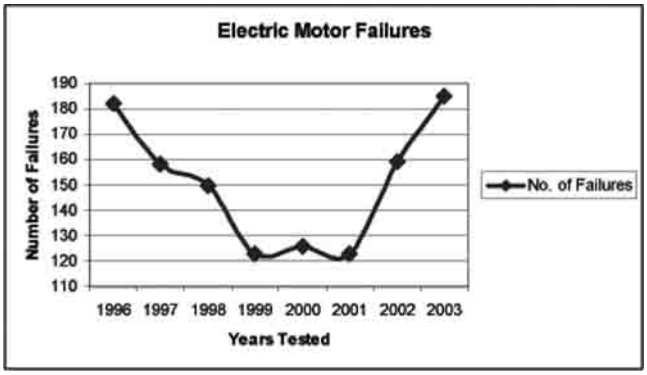


Figure 2: Motor Failures 1996 to 2003
Program started in 1996 and eliminated at end of 2001

Notably, in this study was the fact that electric motor repairs were not eliminated. However, the severity of the remaining repairs was reduced.

Following several years of success (1996 to 2001), new management made the decision to eliminate the motor diagnostic program. In less than 18 months, the conditions that existed prior to the application of the program returned. The result was a dramatic increase in maintenance costs associated with the electric motors, increased unplanned downtime, additional overtime man-hours and emergency work orders.

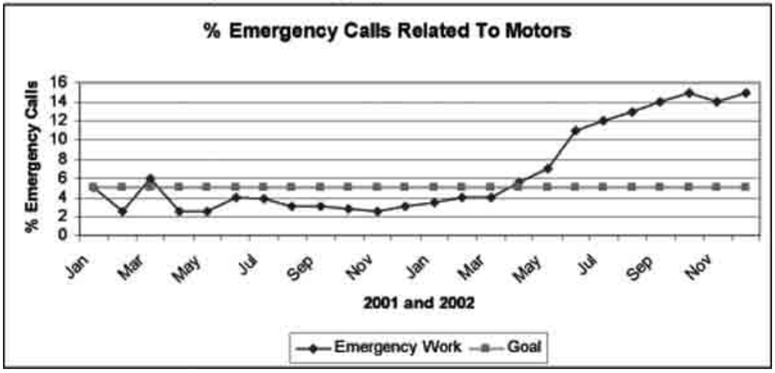


Figure 3: % Emergency Calls Related to Motors

OPPORTUNITY 3: THE APPLICATION OF MOTOR DIAGNOSTICS FOR CONDITION MONITORING

A Midwestern transmission manufacturing facility with an existing, and successful, infrared, ultrasonics and vibration program implemented Motor Circuit Analysis to support the program. The results were fairly dramatic within the first quarter of implementation in 2002:

- Reduction in troubleshooting time of over 50%
- Reduction of 'no problem found' reports, for rotating machines sent to repair shops, by over 80%
- Reduction of repair costs for rotating machines by over 50%, when repairs were proactive. For example: Winding contamination resulting in clean-dip-and-bake versus allowing servo motors to run to failure, resulting in rewind.
- Reduction in motor system life-cycle clost of about 35%

Average maintenance man-hour savings for the first three quarters of 2002 were $30,000 per quarter. Immediately following the implementation of the motor diagnostics program in the middle of the third quarter of 2002, the amount increased to $300,000 per month, not including any production or other cost avoidance.

CONCLUSION

The implementation of an Electrical Motor Diagnostics program, and attention to the health of your motor system, will have an immediate and significant impact on your maintenance program and the profitability of your company.

Richard Borge - Performance Evaluation has been testing electrical equipment for the past 22 years with an assortment of test equipment. Performance has used both static and dynamic tests to help prevent unscheduled downtime. The testing inludes AC/ DC motors of all sizes and transformers.

Howard W Penrose, Ph.D. is the President of SUCCESS by DESIGN, a reliability and maintenance consulting, publishing and training firm. Dr Penrose has over 20 years experience in the electrical maintenance and reliability field. He is the Executive Director of the Institute of Electrical Motor Diagnostics (IEMD.org).

PROPER STEPMOTOR DESIGN BOOSTS EFFICIENCY AND REDUCES NOISE AND VIBRATION

Allen Bennett, General Manager, Intelligent Motion Systems Inc.

Most engineers are familiar with hybrid stepmotors. But, inside the apparently simple mechanism rests a complex combination of laminations, coils, and magnets. Hybrid stepmotors combine the controllability of the variable reluctance motor with the higher torque of the permanent magnet or “canstack” motor.

While low cost is the most no-table feature of hybrid designs, better motor performance and efficiency are also important. New construction techniques now let motor designers use prime-ratio laminations that improve efficiency, lower audible noise, and reduce operating temperatures over standard hybrid stepmotors. The laminations also boost torque output without using expensive electronics.

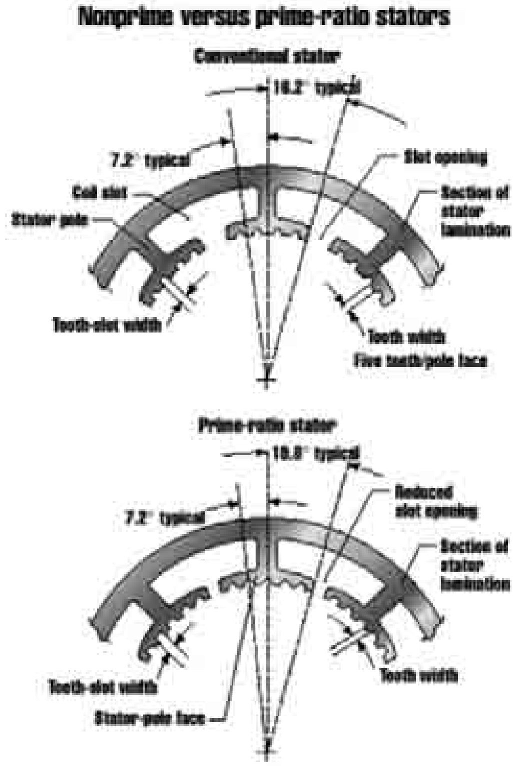
Hybrid stepmotors today are refined versions of the original dynamoelectric machine patented by K.M. Feiertag in 1952. They differentiate themselves from standard electric motors by rotating in discrete amounts or steps rather than continuously. Typically, stepmotors are designed with 0.9, 1.8, or 3.6° full-step-angle increments. The full-step term is used because special driving methods such as half-stepping and microstepping rotate step-motors only a fraction of their full-step motion. The most common hybrid stepmotor in use today is the 1.8° model that requires 200 full steps to complete one revolution.

The “hybrid” term identifies a stepmotor using multi-toothed stator poles and a permanent magnet located inside a multi-toothed rotor-cup assembly. Compared to nonhybrid versions, the hybrid design enhances the magnetic field on the surface of each rotor cup delivering higher torque.

Hybrid stepmotor construction consists of thin sheet-iron laminations layered one on top of another to form two stacks: a stator stack and a rotor stack. The stator stack performs double duty acting as both outer housing for the motor and forming the stator poles along its inner walls.

The rotor stacks form two cup-shape end pieces. The paired rotor cups are assembled with a permanent magnet axially aligned between them forming the rotor assembly. One rotor cup becomes the north pole of the magnet, while the other becomes the south pole.

Prime-ratio hybrid stepmotors like these look and work exactly like the conventional hybrid versions. But the design of their stator-pole laminations improves motor efficiency while reducing noise and vibration.



Conventional stator laminations in hybrid stepmotors have five teeth per pole face. On the other hand, prime-ratio laminations have six teeth per pole face. As both prime and non-prime poles use the same 7.5° spacing between teeth, the prime-ratio pole is slightly larger than the nonprime version. As a result, the open gap between the poles shrinks. The greater quantity of iron in the pole faces helps concentrate the stator magnetic field in the air gap between stator and rotor producing smoother operation with improved efficiency.

Both rotor and stator stacks bear a slot pattern on their surface that resembles teeth on a gear. Rotor teeth possess a 7.2° pitch angle with each tooth and slot measuring 3.6°. This angle creates 50 teeth on the typical rotor. In addition, the teeth between each rotor cup are offset by the width of a tooth. The offset teeth force the magnetic field of the rotor cups into a longer, indirect path used to derive optimal energy from the rotor magnetic field. The intentional misalignment also prevents a loss of torque caused by the magnetic field shorting across the surface of the rotor from one polarity tooth directly to its opposite.

Copper magnet wire wraps around the stator poles forming electromagnetic coils. High-volume stepmotors use plastic-injected slot liners to insulate the coil of wire from the stator. Low-volume motors coat the stator with special insulating materials. The coating process is not as fast as the plastic lining, but saves the cost of an injection mold.

Motor torque is controlled by the interaction between the rotor and stator magnetic fields. The rotor field strength is fixed by the permanent magnet in the rotor. The number of wire turns per coil and the strength of the current flow through the wire determine the electromagnetic field strength of the stator. Smaller-gage wire means higher resistance and, thus, lower maximum current. Likewise, a high number of turns boost coil inductance, limiting the speed of current buildup in the coil. Wire size, the number of turns, and the diameter of the stator windings combine to determine coil resistance, inductance, and coil current — parameters that directly affect motor performance.

The number of teeth on a nonprime-ratio stepmotor is relative to a 7.2° pitch for each tooth. The face of the stator pole should be as wide as possible to direct as much flux as possible into the air gap. More flux in the air gap produces greater torque and less heat due to more efficient operation.

Conventional 1.8° hybrid step-motors contain five teeth per stator pole. Tooth width is proportional to the arc thickness of the pole face. The eight stator poles result in a total of 40 teeth. Openings between poles are used for winding magnet wire around the stators to create the magnetic coils. Slot openings must be wide enough to allow the magnet wire to pass through.

Prime ratio refers to the optimum number of teeth on the stator relative to the optimum number of teeth on the rotor. Hybrid stepmotors listed as prime ratio have one additional tooth per pole face. Shrinking the size of the opening between the poles makes room for the extra tooth. The tooth reduces the magnetic reluctance in the path of the stator magnetic field, putting more flux in the air gap between stator and rotor. The motor becomes more efficient at generating torque.

The number of teeth on the rotor assembly remains set at 50. By adding one tooth per pole, the total number of teeth on the stator increases from 40 teeth (eight poles five teeth/pole) to 48 teeth (eight poles six teeth/pole). So the ratio of stator teeth to rotor teeth with a prime-ratio hybrid stepmotor is 4.8:5 rather than the standard 4:5 of a non-prime-ratio model.

Greater tooth area puts more iron in the pole face. The stator-pole iron is approximately 16% wider in prime-ratio stepmotors than in nonprime versions. The wider tooth focuses more of the magnetic flux into the air gap between the rotor and stator. More effective flux use in the gap reduces flux saturation in the stator back iron, minimizing eddy current losses. Benefits of more tooth area in prime ratio stepmotors include greater output torque with lower audible noise. Conversely, lower operating currents produce the same torque.

The motor operates cooler because of the better efficiency and larger surface area of the stator stack. Cooler running motors impart less heat to the equipment in which they operate. The equipment can, in turn, have tighter tolerances between mechanical components because of smaller mechanical expansion allowances. The better fit between parts limits vibration and noise.

Rotational smoothness improves with prime-ratio stator laminations because the smaller opening between poles reduces torque ripple. Efficiency is better at all speeds but is most visible when speeds are slow. Differences become obvious when prime and nonprime stepmotors are compared side to side. Cogging will be more apparent at slow speeds among nonprime-ratio motors because of the larger stator-pole opening and the smaller flux content in the air gap. Cogging in non-prime motors is also more apparent with lower rotor inertia.

The smooth, slow speeds produced by prime-ratio stepmotors minimize amalgamation of materials when transferring sensitive medical samples or transporting chemicals. Prime ratio stepmotors used in laser marking, engraving, and cutting machines help lower system costs without sacrificing smoothness.

Hybrid stepmotors offer the ability to precisely position a load without using a closed-loop feedback device such as an encoder. Prime-ratio stepmotors attain smoothness at slow speeds without requiring a high-speed current-feedback loop to the controller. Compared to brushless servosystems, smooth motion is possible open loop with much less expense by eliminating the continual monitoring of the motor current.

HOW STEPMOTORS OPERATE

Stepmotors are open-loop devices that rely on the orientation of the rotor and stator teeth for rotation. Teeth on the stator poles and rotor-stack assembly require specific alignment for rotation to begin. Several force vectors created by magnetic flux work together to create rotary motion. In addition to flux vectors that emanate from the stator-pole face, there are also flux vectors between the stator's north/south pole pairs.

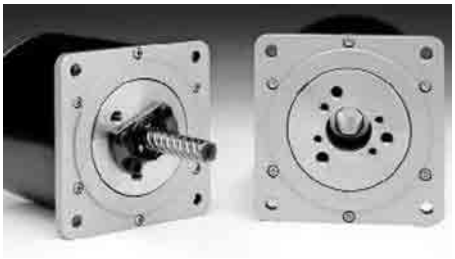
In a typical two-phase stepmotor, two pole pairs make up a phase for a total of eight poles. The phases are labeled A and B. When powered, they create field-strengthening and weakening vectors that work in conjunction with air-gap vectors between stator-pole faces and rotor-cup teeth to rotate the motor in a given direction.

The poles of each phase alternate around the stator at 45° angles and reverse polarity between N and S pole every 90°. For example, if the A-phase stator poles reside at the 12, 3, 6, and 9 o'clock positions, the poles at 12 and 6 o'clock are north while those at 3 and 9 o'clock are south. The B-phase poles sit between the A-phase poles and follow the same N/S pattern.

The magnetic field of the rotor aligns with the magnetic field of the stator coils, locking the rotor in position. The motor rotates when current through one phase changes polarity. The direction of rotation is controlled by the order of phase reversals. As an example, if both phases start with a positive polarity, then reversing the A-phase first will step the motor in a clockwise direction. If the B-phase becomes negative first, the motor rotates one step counterclockwise. If the other phase then reverses polarity, the motor keeps rotating in the same direction and continues to do so as long as the phases alternate reversing polarities.

A stepmotor "driver" controls the polarity and voltage supplied to the phases. Many drivers supply a voltage 4 or more higher than the operating voltage of the motor when the polarity is switched. The higher voltage helps overcome coil inductance by forcing a faster buildup of current through the coil, thus maximizing torque. A chopper circuit in the driver limits total current to the preset operating value for the motor. Drivers typically require a trigger pulse or "step command" to produce the change in polarity.

The stator and rotor teeth help concentrate the magnetic flux in the air gap between them. The strength of the flux vectors in the air gap, and thus motor torque, is directly proportional to the energy of the stator coil and the amount of tooth iron on the stator pole. Larger tooth surface areas in the air gap also boost flux intensity and, ultimately, the amount of torque the motor generates. The result is improved mechanical time constants with faster motor acceleration.



The inside-out stepmotor (IOS) construction places the rotor assembly to the outside while the stator remains in the middle. The unconventional design lends itself well to through-hole applications where pipes, wires, and conduits must pass through the centerline of the stepmotor.

THE INSIDE-OUT PRIME-RATIO STEPPER

A new patented design by Intelligent Motion Systems Inc. is the opposite of conventional hybrid stepmotor orientation. The inside-out stepper, or IOS, places the rotor assembly on the outside of the stator assembly, This orientation makes it possible to hollow out the core of the motor creating a "through hole". Such a feature invites innovative solutions for linear positioning, rotary, and gearbox systems.

The IOS delivers up to 1,200 lb of linear force at speeds <1 rps with repeatable accuracy to ±3 arc-min. In addition, the prime-ratio lamination architecture of the IOS42 augments motor torque and efficiency, reduces low-speed agitation, and significantly enhances smoothness of rotation.

Compared to traditional approaches, IOS motors let designers eliminate components to simplify mechanical designs, shrink footprints, and lower overall cost.

RADIAL GROWTH TESTING

H. Eric Sonnichsen, Test Devices Inc.

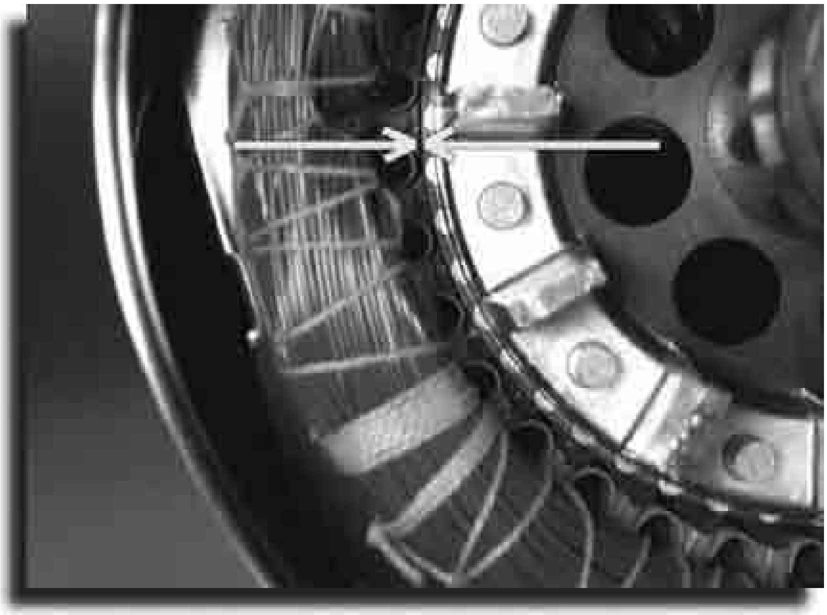


Figure 1 - Motor Gap

Due to higher speed requirements, it has become a technical challenge to design high-speed rotating equipment to withstand the rotational stresses imposed on spinning components. Test Devices has the ability to quantify the diametrical or radial growth of high RPM rotating parts. The forces on rotating parts grow alarmingly fast as rotational speed increases. This can lead to substantial diametrical growth which must be taken into consideration during the design, particularly, if touching a nearby stationary component is possible.

Electric motors, for example, are particularly sensitive as the air gap between the rotor and stator is critical to the performance of the motor. Designers must ensure that the rotor/stator air gap is not consumed due to growth of the rotor from centrifugal force, thereby threatening mechanical contact and motor failure. Conversely, too much gap, and one reduces motor performance. An example of Test Devices' centrifugal growth measurement capability, known simply as Radial Growth Testing, is a recent test done for a high speed motor manufacturer. TDI's measurement capability enabled the customer to document the growth their component experienced under centrifugal load at various speeds on up to operating speeds and optimize the distance between the rotor and stator. The Test Devices' supplied data enabled the customer's engineers to balance the flux density, manufacturing tolerances and material selections to optimize the motor/stator air gap. The result was a more efficient motor design with reduced warranty costs.

Increasing speeds, thus, increased centrifugal stress, increases the diametral growth. Test Devices' centrifugal growth measurement capability gives designers precise information on the amount of growth experienced during rotation. This growth is comprised of two components which Test Devices can determine separately. Growth shown only at speed is said to be "elastic growth" which fully recovers. Similar to a rubber band returning to its original shape after being stretched; rotating parts experiencing elastic growth return to their original dimensions after rotation is stopped. Plastic growth, or growth which results in a permanent deformation in the component's dimensions, occurs when the centrifugal force overcomes the component's material strength that is trying to hold its original shape. After undergoing plastic growth, a rotating component can never return to its original size.

Radial growth of rotating equipment also affects the axial length of whole assemblies. Due to Poisson contraction, when the outside diameter (OD) of a rotating component grows, it may at the same time axially contract to accommodate the radial growth. The resulting change in axial length can loosen lamination stacks and deteriorate motor performance.

Test Devices Inc. has developed test methods to assist designers in measuring these critical deflections (radial growth) during rotation at actual design speeds and temperatures. Test Devices' engineers can define the elastic and plastic components of centrifugal growth up to and including the burst speed. By using this data, our customer's product engineers can improve equipment designs to obtain better performance and/or durability.

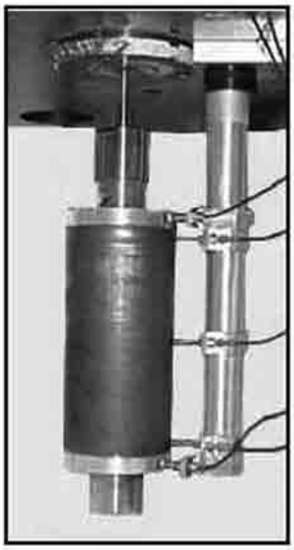


Figure 2 - rotor w/proximity sensors

PROCEDURE

Test Devices' spin facilities utilize magnetic, fiber optic, or laser proximity sensors, to measure static/dynamic radial growth of high speed rotating components. Using several sensors enables growth monitoring of multiple rotor components to identify which elements experience the most extreme growth and at which speeds growth becomes critical to the detriment of the rotor/stator air gap or failure of the rotor.

This technique can be employed in testing rotor assemblies comprised of differing materials and interrupted surfaces. For instance, many magnetic rotor assemblies include not only stacks of laminations but also retaining assemblies designed to restrain the growth of the laminate stacks at speed. Thus, it is important to not only measure the growth of the laminate stacks, but also the performance of the retaining assemblies.

The sensors are individually calibrated and aligned with the rotor surface to be measured to ensure accurate measurements. Sensor to rotor gap is typically determined based on the customers expected growth. Once the probes are installed, the rotor is spun to speeds to elicit radial growth. Growth measurements are taken not only during acceleration but also during deceleration to determine the extent of permanent deformation.

The picture (above right) shows a typical radial growth test setup with multiple growth sensors monitoring different sections of the electric motor rotor.

TEST EXAMPLES

The following data graphs from a radial growth test are examples of work done at Test Devices' facility. Radial growth testing has been performed on a wide variety of products such as electric motor rotors, composite flywheels, alloy material samples, jet engine rotors, and automobile starter armature comutators.

EXAMPLE 1

The graph below shows a growth test of an automotive electric motor rotor at 392° F. The red line indicates the growth of the rotor OD at speed. Notice that there was little appreciable growth until 3000 rpm. From 3000 rpm to approximately 7000 rpm growth was consistent vs. speed. However, above 7000 rpm the growth becomes exponential as the rotor material is unable to overcome the centrifugal load. For this customer, rotor "failure" happened when the OD grew more than 8 mils, indicating that the rotor performance in service would have been substantially reduced.

EXAMPLE 2

The next four graphs are growth data from a characteri-

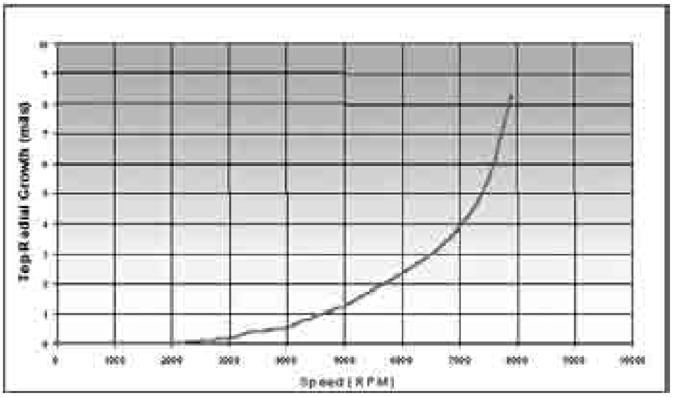


Figure 3 - Growth Chart

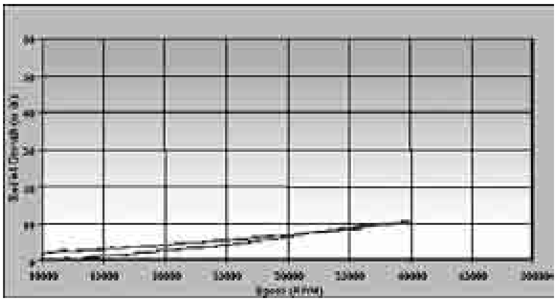


Figure 4
Run #1
10 mils total growth and 2 mils of permanent growth

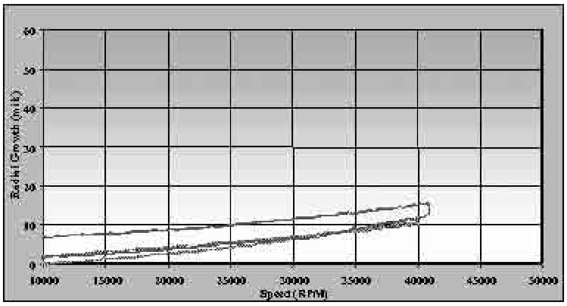


Fig 5 - motor gap growth
Run #2
14 mils total growth and 5 mils of permanent growth

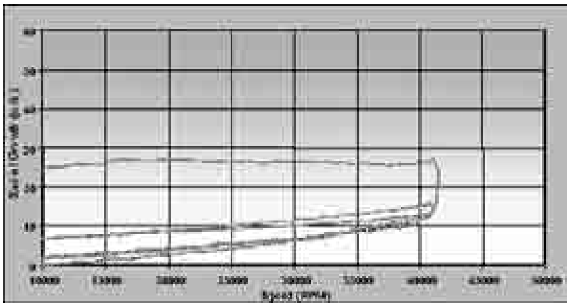


Fig 6 - motor gap growth
Run #3
20 mils total growth and 17 mils of permanent growth

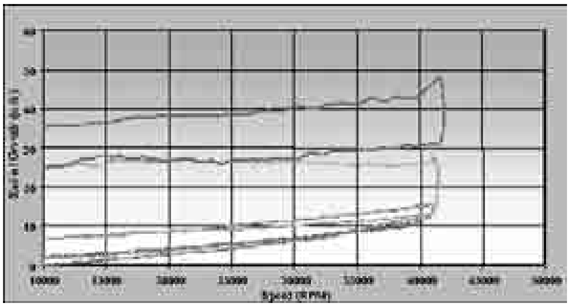


Fig 7 - motor gap growth
Run #4
14 mils total growth and 5 mils of permanent growth

zation test of a new steel alloy, tested in a rotor coupon configuration. The graphs are growth data taken from four sequential tests of the same rotor. With increased speeds, the steel alloy yielded substantially, resulting in considerable "plastic" growth of the OD. This material was very ductile (easily stretched), allowing it to continuously yield even when substantially higher centrifugal loads were encountered. Many less ductile alloys would have failed earlier from the increased stress. The customer was able to use this test data to calibrate an electronic model to better predict the growth that actual engine components would see during operation.

BENEFITS AND APPLICATIONS

Radial growth testing can be an invaluable tool whenever the growth of any type of high speed rotating component is of concern. This technique can be used to verify the growth caused by centrifugal stress, not only to understand rotor/stator interaction but also to verify material properties for improvement of predictive models. With the data provided by Test Devices' Radial Growth test, a product's important parameters can be optimized for cost, performance and reliability.

SPIN TEST SYSTEM DRIVES: AIR TURBINE AND ELECTRIC MOTOR COMPARISON

H. Eric Sonnichsen, Test Devices Inc.

The comparison between spin system electric drives and air turbines is analogous to the choice between electric and gas-powered automobiles. Both have advantages and disadvantages which must be considered before deciding which is appropriate for an application.

At first glance, the electrical drive option appears to be the most attractive for Spin Pit Systems, including Dynamic Spin Rigs. Electric drives use clean energy, some of which can potentially be saved during the braking phase of testing. Compressed air drives require additional hardware (compressor, piping, valves, etc.) which appear to add cost and maintenance.

However, with over 30 years of experience in designing, building, and using spin test systems, Test Devices knows that the choice of drive system is critically important to any spin system. Most Spin-Pit drive systems must handle a wide range of test requirements including: over-speed (proof), burst, Low Cycle Fatigue (LCF), & High Cycle Fatigue (HCF). Outlined below are some of the issues one must consider when choosing a spin test system (spin-pit).

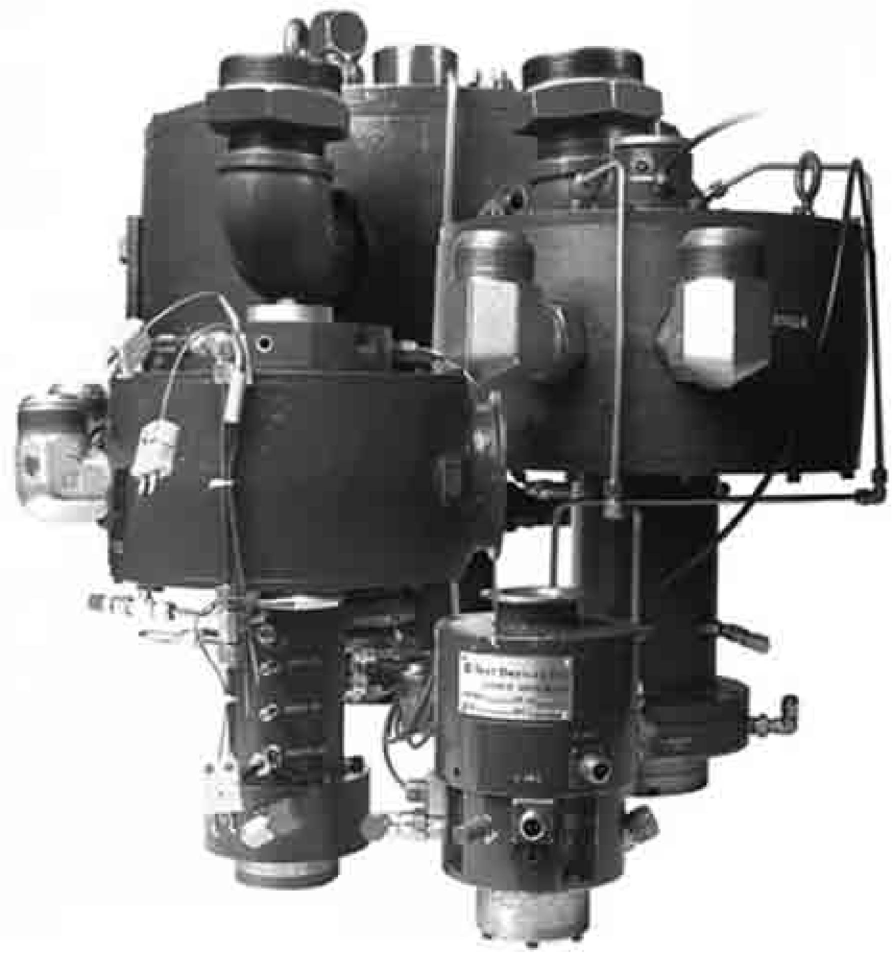


Figure 1

FLEXIBILITY

Air turbines are compact drive systems which permit easy mounting and removal from the Spin Testing Chamber, requiring only a few connections or disconnections. The ease of switching turbines allows customers who require testing in multiple speed ranges (i.e. 10,000 rpm, 30,000 rpm, 50,000 rpm) to increase efficiency by performing 2-3 tests of different speed ranges in the same day.

Electrical drive systems have only one drive (controller)/motor combination, which must accommodate the system speed range required. This restriction is not convenient for the wide range of applications requiring multiple speed ranges inherent with Spin Test Systems.

Another great advantage of spin test systems with air turbine drives is the ease with which the system can be upgraded to new turbines to handle different speed range requirements which are inevitably necessary. Upgrading an electrical drive system is much more difficult and requires that the complete drive (controller) be replaced at a sizable investment. Before selecting an electric drive system, the customer must decide if any future upgrades or changes will be necessary to accommodate requirement changes.

ROBUSTNESS

Based on extensive experience, Test Devices has designed robust air turbines used for testing jet engine components to failure. The turbines typically perform the test without incident and only rarely does specimen failure result in damage to the turbine, and then only relatively minor. Test Devices has burst parts weighing many hundreds of pounds with little or no damage to the turbine. When there is damage to the turbine, it is generally necessary to replace only damper components (seal,

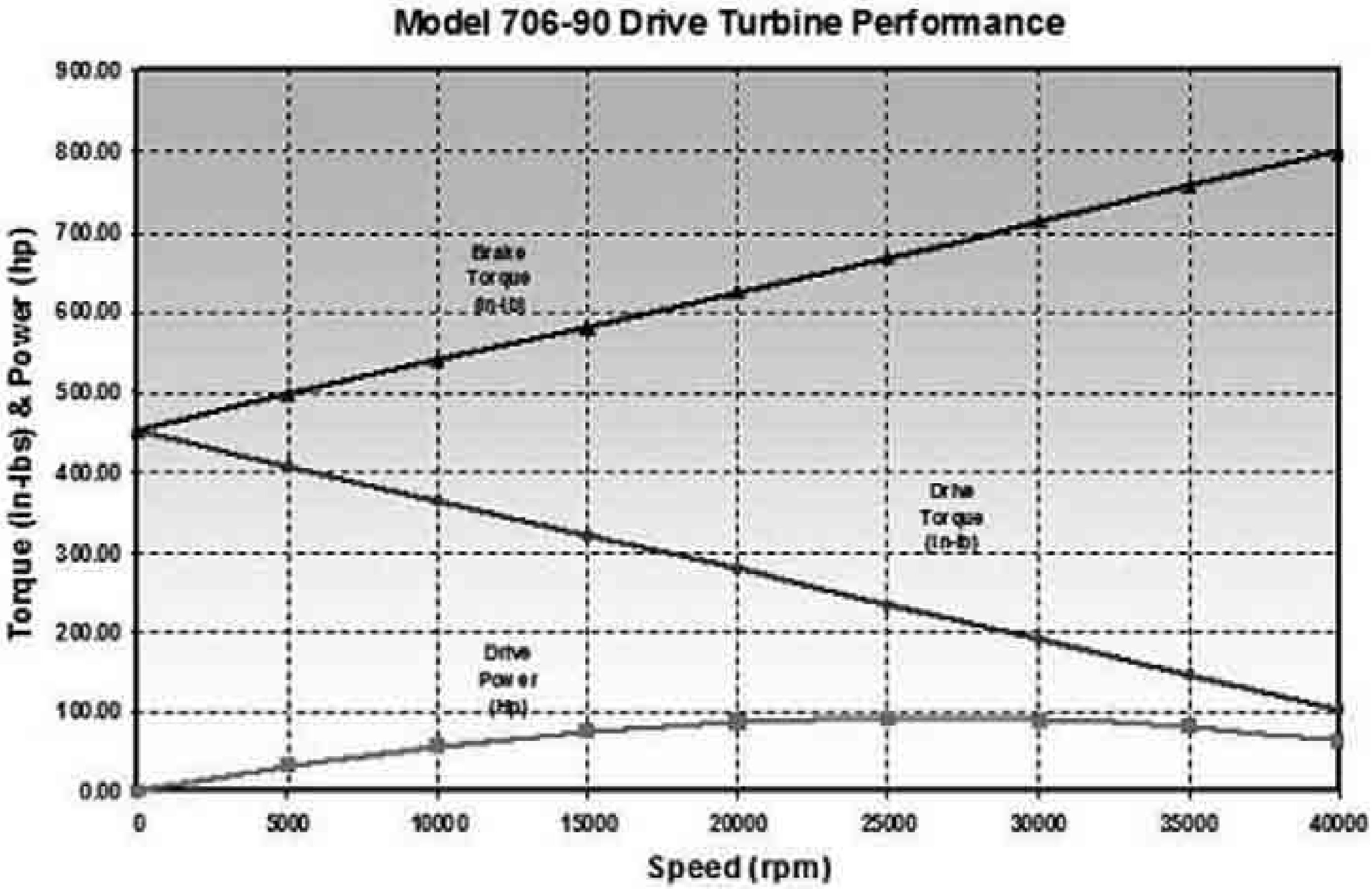


Figure 2

bushing, wear plate). This is easily done with the turbine mounted on the spin chamber or a workbench, and the drive is ready for service in a matter of hours.

Electric motor drive systems include a gearbox unit, which is damage prone during high-energy bursts common during failure of jet engine components. The gears inside the gearbox assembly do not tolerate the shock well resulting from a burst event, resulting in extensive damage. Replacement of these gears is not only very expensive but also delays testing programs due to the long lead time required for delivery of replacement parts.

Operators of electric motor systems have confirmed that problems with the drive (controller), motor, or gearbox require supplier support. The user is unable to make most repairs, which necessitates a visit from a factory representative to investigate the problem. If the difficulty cannot be resolved on site, vital components of the drive system must be sent to the OEM's shop for repair. These repairs, generally unexpected, cause considerable interruption in the use of the system and essentially result in the DSR sitting idle for many weeks while the drive is repaired.

Conversely, as discussed above, in a high percentage of the cases where an air turbine is damaged from a rotor burst, the user can repair the turbine internally in a very short period of time. Furthermore, other tests can be run with another turbine while the repair is taking place.

RELIABILITY AND SAFETY

Spin testing is characterized by rotating parts with high kinetic energy. For safe and reliable operation, the drive system must be able to be slowed to 0 rpm in the shortest period of time. Rapid braking is required during any of the following:

- emergency event;
- rotor high vibration;
- loss of electrical power; or
- rotor cracking.

The spin pit, which uses air turbines, has a redundancy feature that decelerates the rotating part to zero even when electrical power is interrupted. Conversely, electrical drives cannot be controlled when power is lost, and rotor speed decelerates very slowly. Only bearing friction is available to slow the test specimen, which can be a very long time for parts with large inertias. This long coasting period can cause severe damage to the rotating parts or the system itself to say nothing of the lost equipment time.

Furthermore, many electric drive systems incorporate a drive belt which transmits torque from the electric drive to the spindle head. Drive belts break occasionally, resulting in the operator having no ability to slow the speed of the rotating part. Some operators have had to wait literally days for large inertia parts to slow to 0 rpm after a belt failure. Additionally, the spindle head is often damaged requiring extensive repairs.

ELECTRICAL NOISE

Many spin-pits are used to test instrumented (strain gages, thermocouples, pressure transducers) engine components for strain surveys and low & high cycle fatigue. To properly perform this testing successfully, signal integrity is paramount to ensure the accuracy of resultant data. Because signal strength from these sensors is low, they are susceptible to outside interference, and degradation from interference and electrical noise can be detrimental and costly to good results.

Air turbines, because they are mechanically driven devices, provide no electrical interference and do not degrade the signal output from instruments mounted to the test disc.

Electrical drives by their very design introduce substantial electrical noise to the spin chamber environment. Every electrical drive system, especially variable frequency drives systems; double convert the electrical signal from the power line to the electrical motor. This induces high electrical noise in the power line and inside the test facility by electromagnetic radiation. Even with excellent shielding and filtering, this problem still exists along with the presence of high harmonics content, which cannot be eliminated.

Electrical drive noise is a critical issue for blade characterization tests when investigating high frequency modes with very low signal levels. Through the path where signals are transmitted, including slip rings mounted on the drive head or gear box, noise accumulates and negatively affects the signal-to-noise ratio to a level that is not acceptable for this type of testing.

The following is an excerpt from a Vishay Measurements Group (supplier of strain gages) paper on electrical noise interference with strain gages which speaks directly to this issue.

"Virtually every electrical device which generates, consumes, or transmits power is a potential source for causing noise in strain gage circuits. And, in general, the higher the voltage or current level, and the closer the strain gage circuit to the electrical device, the greater will be the induced noise."

Therefore, a customer can have more confidence in the data taken from an instrumented test run with an air turbine than with an electrical drive.

LCF TESTING EFFICIENCY

A spin chamber drive intended for LCF service has to accelerate and brake the test rotor inertia in the shortest possible time to maximize operating cycles per day. Cycle rate is productivity. Longer cycle times delay engine development programs, and thereby cost the user many times more than any savings that might accrue from operation of electric motor drives.

Air turbines are the best drive choice for LCF testing because their high operating speed and inherent torque characteristics give short cycle times and are relatively simple mechanically.

Air turbines give high drive torque at low speed, with lower torque at high operating speed. Brake torque is high at all speeds and is an important reason for the cycle time advantage of air turbines. The high brake torque is also very critical when the speed of a rotating part must be reduced to 0 rpm very rapidly due to high vibration, a developing rotor crack, or loss of electrical power. The previous graph below shows the drive and brake torque of a typical Test Devices air turbine operated at 90 psi nozzle pressure (for model 706-90 shown).

The graph plots both torque and horsepower as a function of speed. Note that torque is linearly related to speed, with both drive and brake torque equal at zero speed. Notice also that drive horsepower peaks when the torque is exactly half the at-rest torque. The speed at this point is called "design speed" and is the point where the velocity of air leaving the drive rotor is most nearly zero.

Torque is produced by the relative velocity between the rotor and the air exiting the nozzle ring. In the drive direction, that relative velocity decreases as the rotor speed increases. In the brake direction, the opposite is true and the relative velocity increases as speed increases.

Calculation of cycle time for an inertial load equating the first differential of speed with the speed function and separating variables, the differential time can be integrated to show that acceleration time from rest is:

Acceleration time = ω*I/* (ln(T_f/T_o)/(T_f-T_o)) (for linear variable torque)

Where:

T_o = Torque at zero speed

T_f = Torque at Peak Cycle Speed

ω = Cycle Speed (radians per second), and

I = Inertia (lb-in-sec^2)

Because LCF cycles don't start from zero speed, and because acceleration is not linear, one must calculate acceleration time from zero speed to peak speed, calculate acceleration time from zero speed to the cycle minimum speed, and subtract the two times. The difference is the acceleration time from minimum to maximum speed. The braking time is calculated the same way, but the torque is different, so the calculation is repeated using the brake torque values.

Table 1

EXAMPLE 706 TURBINE CYCLE TIME	706-90
90 PSI FLOW	1540
INERTIA (LB-IN-SE C2)	1.03
STALL TORQUE (LB-IN)	452
MAX SPEED TORQUE	104
MAX SPEED	40,000
STARTING SPEED (RPM)	3,700
FINAL SPEED (RPM)	37,000
DRIVE IDLE TORQUE (LB-IN)	419.67
DRIVE FINAL TORQUE (LB-IN)	130.46
BRAKE IDLE TORQUE (LB-IN)	483.93
BRAKE FINAL TORQUE (LB-IN)	773.15
FINAL SPEED Hp (DRIVE)	76.62
FINAL SPEED Hp (BRAKE)	454.07
ACCEL TIME TO START	0.92
ACCEL TIME TO FINISH	15.43
NET ACCEL TIME (SEC)	14.51
BRAKE TIME TO STOP	6.67
BRAKE TIME IDLE TO STOP	0.85
NET BRAKE TIME (SEC)	5.82
NET CYCLE TIME (SEC)	20.33
NET BRAKE TIME (MIN)	0.34

Electric motor drive torque is limited by the maximum available air gap flux density and, therefore, electric motors produce constant torque. Power is the product of torque and speed. Thus, electric motors give half power at half speed, 1/10 power at 1/10 speed, etc.

Using the calculation shown below, a 75Hp, 40000 RPM constant torque drive would give a much longer cycle time:

Constant Torque Acceleration:
Acceleration time (for constant torque) = $(\omega_f-\omega_0)$*I/T
Cycle time = 2 x Acceleration time.
Net cycle time = 61 seconds
Where:
T = Torque (117 in-lb at 75 Hp)
I = Inertia (1.03 lb-in-sec^2)
S_0 = Peak Cycle Speed (rpm)
ω_0 = Peak Cycle Speed (radians per second) = S_0*2 p/60
S_f = Peak Cycle Speed (rpm)
ω_f = Peak Cycle Speed (radians per second) = S_f *2 p/60

Cycle time for a constant torque drive (electric motor) is much longer than for an air turbine of the same nominal power. For example, consider the 706-90 drive turbine from the calculations above. It produces 90.3 horsepower at design speed, 76 Hp at 37000 rpm. With an inertia of 1.03 lb-in sec2, the cycle rate would be 20.33 seconds. Because of its favorable torque characteristics, an air turbine produces about 3 times as many test cycles as an electric motor with the same power rating (20.33 seconds vs. 61 seconds from above). With an air turbine drive system the Spin Test System will operate at optimum performance for the desired speed range by selecting and installing the proper turbine. Electrical drives do not allow the customer this flexibility, because the system is fixed by the initial design.

SUMMARY

The flexibility of the air turbine drive is particularly important to users who would like to use one spin pit for many different speed range and testing profiles.

The speed of TDI turbines can also be precisely controlled which is critical for any HCF testing program. TDI turbines coupled with the speed control system can control rotor speed with an accuracy of +/- 0.01% of the full speed scale. Also the turbines ca

THE SELECTION, CONNECTION, REVERSING AND REPAIR OF ELECTRIC MOTORS

Robert W. Lamparter

Selecting a motor and connecting the electricals are the first challenges encountered after purchasing that long coveted machine tool. There are several types of single phase AC motors in current production in the U.S., but only two types are commonly used in powering our equipment.

TYPES OF MOTORS

For the purpose of clarity I will describe the features of the common types of fractional horsepower motors.

Universal or series motors are those having brushes and a wound rotor. An example of this type is that found in a portable drill or a Dremel tool. They are also distinguished by their noisiness.

Induction or shaded pole motors are the ones commonly sold in window fans. They have a solid (squirrel cage) rotor and start slowly, gradually building up to speed.

Repulsion motors are old and less common. Being old, they tend to be on the large size. They have a wound rotor and brushes electrically connected to each other but not to the stator windings. A large motor with brushes (assuming that the nameplate doesn't indicate a DC motor or generator) is the tip-off that you are likely examining a repulsion motor. This type of motor can be reversed by shifting the position of the brushes. Having seen one of these powering a large drill press in a local blacksmith's shop, I would not recommend investing in a repulsion motor, since the remaining types of motors to be described will do the job much better.

The final three types of motors are the ones most suitable for powering home shop machinery: split phase motor (split phase start - induction run), capacitor start motor (capacitor start - induction run), and capacitor start-capacitor run motor. All are distinguished by a solid squirrel-cage rotor and an audible click when the motor has been turned off and is slowing down. The split phase motor has no cylindrical hump on the outside for the capacitor; the other two types obviously do. The capacitor start-capacitor run motor will have either two capacitor humps or will have a capacitor with three separate electrical connections. By the process of elimination, it should seem obvious that a capacitor start motor will have a single capacitor that has only two electrical connections.

All of the motors described operate on house current, which is single phase. Three phase motors are commonly found on used industrial machines and will not run on house current without an expensive rotary phase converter. The solid state phase converters are cheaper, but our local electric motor rewinder intimates they have a tendency to burn out. Because of a lack of experience with three phase power, I have found it best to avoid these motors. The maker's plate with the electrical information states whether the motor is single phase or three phase.

RECOMMENDATIONS ON TYPE AND SIZE OF MOTOR

Capacitor motors have a much greater starting torque than split phase motors. I prefer to use capacitor start motors on all tools except bench grinders. When the starting load is heavy, a split phase motor will take a long time to come up to speed. There are two problems with this. One is that a great deal of current is drawn, causing the shop lights to dim. The other is that the starting windings are a lighter gage wire; with repeated two- or three-second starting periods, the starter windings will eventually burn out.

Split phase motors are considered to be adequate for easy starting tools, such as grinders, drill presses, jigsaws and the like. I have found the 1/3 hp split phase motor on my old Delta drill press to be adequate for all but the higher speeds. If I had an industrial drill press with a No. 2 or No. 3 Morse taper, I would want a 3/4 or 1 hp motor. A respected practitioner of our craft is quite satisfied with a 1/3 hp split phase motor on his 9" South Bend lathe but admits to doing only light turning. I had a 1/2 hp capacitor motor on my 12" Clausing lathe. This never seemed to slow down even under heavy cuts, but a winding eventually burned out. From this experience, I infer that something more robust than a 1/2 hp motor is needed for a 12" lathe. I suspect that a 3/4 hp motor would have been adequate, but a 1.5 hp motor was the only used motor available when the old one burned out.

ADEQUACY OF SHOP WIRING AND THE MERITS OF 220-VOLT OPERATION

Next comes the job of wiring the motor. First look on the motor's information plate for the operating amperage and determine if the shop wiring and fusing are adequate. According to Sears and Roebuck's "Simplified Electrical Wiring". the starting currents of motors are roughly three times the operating current listed. For practical purposes, unless the starting time of the motor is prolonged by a heavy load, the operating current of the motor will determine if the breaker is going to trip. As an example, at 110v, a typical 1/2 hp motor will operate on 7 amps or less, but will draw 22 amps when starting. In my old house which had 15-amp breakers, I never overloaded the circuit with a 1/2 hp motor.

If you acquire a piece of equipment that exceeds your shop's electrical capacity, you're going to have to do some wiring. The purchase of my air compressor presented me with this problem. At 110v its operating current was 17.8 amps and the 15-amp breaker would trip rather frequently. At the time, I didn't know how easy it was to add a circuit breaker and run a 220v line, so I tapped into one of the 20-amp circuits in the house and used 12-gage wire to run a new 110v line to the shop.

A few years later, a machinist friend of mine introduced me to the concept of using 220v current for the machines. I had always assumed that heavy wires such as that used on dryers and ranges was needed for 220v work. Not so! Those wires are heavy because dryers and ranges pull currents in the range of 30 and 50 amps, respectively. Actually, a reduction in the wire gage may be enabled by running a motor at 220v. When a motor is rewired to run at 220v, its operating amperage is halved. Thus, the compressor that pulled 17.8 amps at 110v only drew 8.9 amps at 220v. When I finally ran my 220v line to the shop, I used a 15-amp breaker and 14-gage wire. What a difference it made in how quickly the compressor started. On motors that will operate at either 110v or 220v, I prefer to run them on 220v since there is much less dimming of the lights and much quicker starting at this voltage.

For future reference, remember that fuses and circuit breakers protect the wiring of the house from overheating and burning while inside a wall, and therefore are sized to be compatible with the house wiring they protect - not the machine connected to it. This is why it's dangerous to just put a larger fuse or breaker on the circuit to your shop without improving the wiring. 12-gage wire will carry 20 amps, 14-gage wire 15 amps, and 16-gage wire 10 amps. Home wiring is fairly straightforward, but the details are beyond the intent of this article.

INTERNAL WIRING CONNECTIONS: CHANGING FROM 110V TO 220V OPERATION

Next we turn our attention to the internal wiring arrangements of split phase and capacitor motors. They are almost identical except the capacitor start motor has a capacitor. Both motors have two types of windings - starter windings and running windings. The starter windings determine the direction of rotation. They are of a light gage wire since they are only used briefly for starting and then are disconnected from the circuit by a centrifugal switch when the motor is almost up to speed. The click heard when the motor is slowing to a halt is the centrifugal switch clicking the starting windings back into the circuit. The lead numbering I present in my diagrams, Figures 1 through 4, is used in three motors in my shop, all of which are of different manufacture. One of them is British in origin. I assume the numbering system is universal, but I can't be assured of this since I haven't found these diagrams in print. If there is a wiring diagram on your motor, so much the better; you don't need me. If not, I'll give you as many tricks to identify the leads as I can:

Lead No. 8 is the one usually attached to the capacitor or centrifugal switch. Leads No. 6 and 7 are usually buried somewhere in the motor and aren't seen. If three leads are twisted together, they probably represent two running winding leads and a starting winding lead. According to an article in "Model Engineer" the starting windings have a slightly higher resistance than the running windings. On my Brooks 1.5 hp motor, the starting windings have a resistance of 2.2 ohms and running windings have 1.2 ohms of resistance. Take the utmost care in making these measurements since a dirty contact will alter the measurement. If only four leads come to the terminal board, two are probably running winding leads and two are probably the starting winding leads No. 5 and 8. I can't cover all the possibilities, but that should help you in getting started.

Figures 1 and 3 show the comparison between a motor set up to run on 220v versus one wired to run at 110v. Note that the starting windings are connected in series with one of the running windings when the motor is wired to run at 220v. A few years ago when I bought a used 3/4 hp motor to replace the three phase one that came in my Hardinge mill, a less than attentive employee at the motor rewinders instructed me to connect starting winding leads No. 5 and 8 to running winding leads No. 1 and 4 - in essence, to the full 220v input. The motor ran fine for two months, and then one time on starting, it smoked, made a horribly loud vibrating noise, and rotated at only a fraction of its normal speed. Fortunately, only the capacitor had failed. When I purchased the new capacitor, I inquired about the wiring connection on this motor since it was different from two others in my shop. The owner of the rewinding shop instructed me to place the starting windings in series with the running windings so that they would absorb some of the current going to the starting windings and capacitor, prolonging their life expectancy.

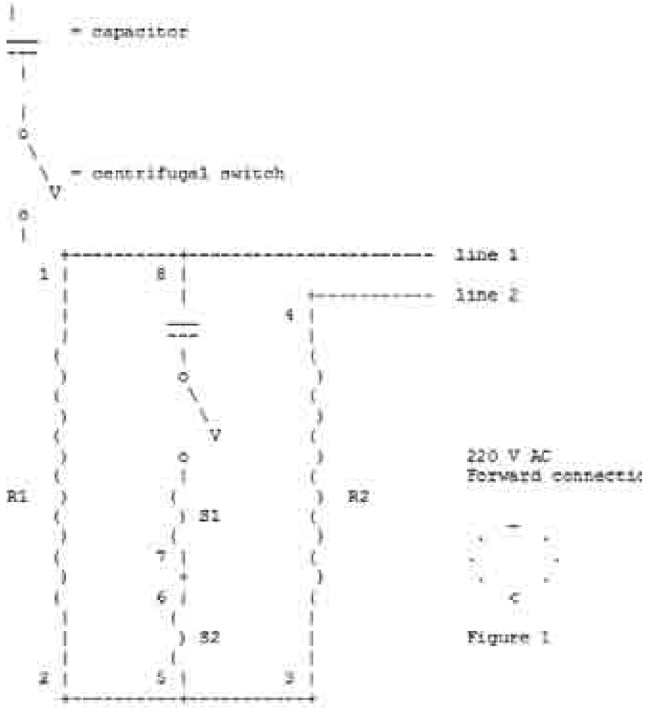


Figure 1

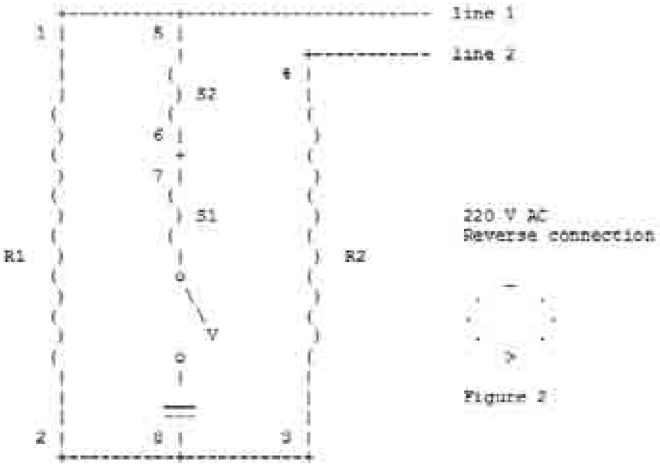


Figure 2

Having converted a motor to run on 220v, it is worthwhile to test it at 110v first. If wired correctly, it will run at a somewhat slower than normal speed.

R = running winding
S = starting winding

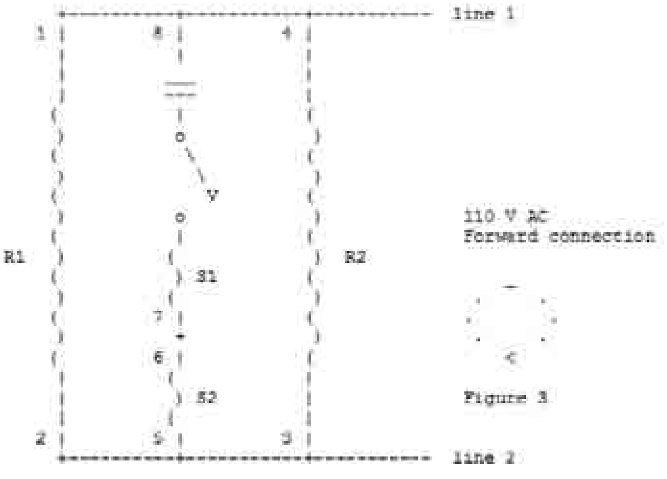


Figure 3

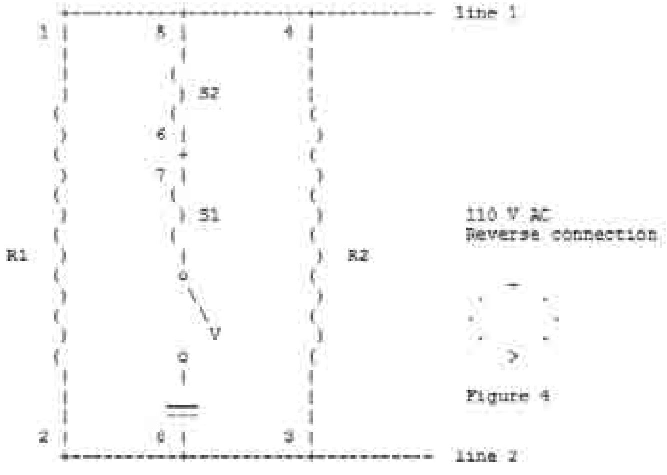


Figure 4

REVERSING THE ROTATION AND WIRING DRUM SWITCHES

Reversing the rotation of a motor is often desired. From Figures 1 through 4, it is evident that reversing the connections of the starting winding leads No. 5 and 8 is all that is necessary. In Figures 5 and 6 are the wiring diagrams for the terminals in a drum switch controlling a 220v motor. Figures 7 and 8 show the same switch wired for a 110v motor. Note that the only difference in the internal wiring of the drum switch between 110v and 220v is a link between the terminals on the lower left. Pay attention to the fact that in Figures 7 and 8 Line 2 is the hot or live wire.

DRUM SWITCH LEGEND: There are 9 connection

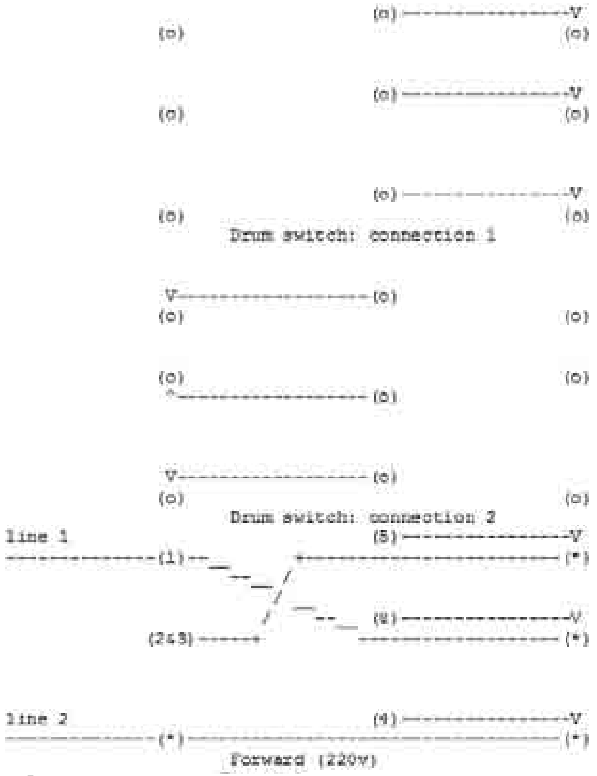


Figure 5

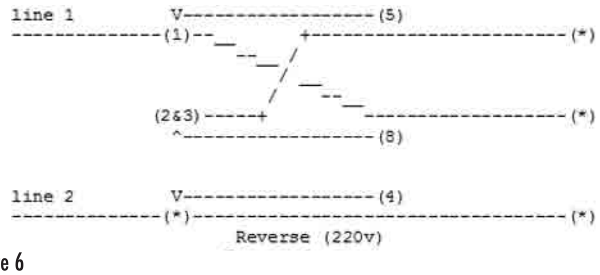


Figure 6

points depicted. The central 3 points connect either to the right 3 points, as shown first, or to the left 3 points, as shown second. In Figures 5 through 8, some of these points are wired together, and some are connected to wiring points in the motor. These motor wiring points are numbered the same as they were in Figures 1 through 4.

Several years ago, when the previously mentioned 1/2 hp motor in my lathe burned out, I didn't have a reversing switch but only the standard single pole wall switch controlling the current flow. Thoughtlessly, I had connected this switch to the neutral (white) lead. When the motor started to hiss and smoke, I quickly flipped the switch off. Much to my alarm, the motor continued to hiss, smoke and run! When the winding burned, it shorted to the motor frame and a circuit was completed from the hot wire through the remaining windings to the ground wire. I had to dash to the breaker box to shut off my lathe. (Thank goodness I've never tried to save a few cents by buying electric cord without a ground wire or, in this case, I might have "been"

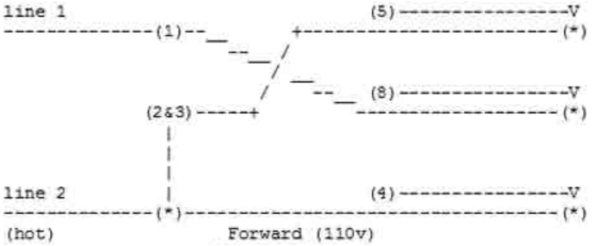


Figure 7

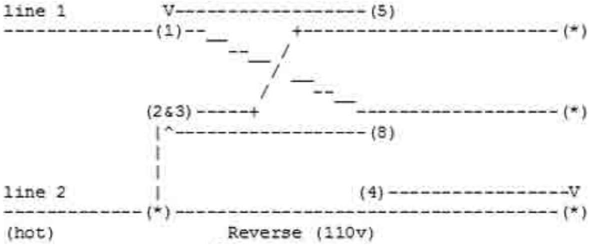


Figure 8

the ground wire.)

This same flow occurs in the wiring of the drum switch for 220v since both of the lines are hot (live), and Line 1 is directly connected to the motor without an intervening switch. In my own shop, I solved this problem with a magnetic starter; more on these later. Figure 9 shows an alternate type of drum switch configuration which may be encountered. By now you should have some idea of how to arrange the connections, so I won't illustrate these. If you're still in your salad days and can't afford a drum switch, an alternative is to utilize a four-way switch, the type used in household wiring when three or more switches control the same circuit. The electrical connections are illustrated in Figures 9 through 13.

There are two types of four-way switches - cross type and through type - and you'll have to determine which type you have with an ohmmeter or test lamp. I have illustrated the connections for a 110v motor only, but there's no reason the same setup couldn't be used for 220v operation. With a four-way switch you'll need a separate switch to turn the motor on and off.

While we're on the subject of making-do, I'll pass on another pearl. Shoe eyelets make nice electrical connectors. Just wrap the bare wire around the post and crimp. Sometimes a rap in the hole with a center punch is needed to expand it so that it will fit over a screw terminal. Next you'll need four- or five-wire "cable" to run from the switch to the motor. Since cable is not available in my small town, I've made my own using 5/8" ID clear plastic tubing and different colors of 14 or 16 gauge multi-strand wire. If the cable isn't too long, a coat hanger can be used to pull the wires through.

MOTOR PROTECTION AND MAGNETIC STARTERS

Motor protection is often neglected. The fusebox or circuit breaker does nothing to protect the motor in case of an overload. They just protect the house wiring so it doesn't start to burn while hidden in a wall.

Many used machines come with the motor protection device still attached. In some cases they are manual devices and in others they are magnetic starters. Almost invariably these devices are set up for three-phase operation, so you'll have to follow the instructions inside the lid to make the conversion to single-phase operation and the proper voltage. You'll have to buy one or two heater elements to match the operating amperage of the motor to be protected. A list of the parts numbers for the heater elements is usually printed inside the lid with the connection instructions. On magnetic starters, also look at the label on the magnetic coil to be sure it's the correct one for the voltage you intend to use. The protection device is placed in the circuit between the plug and the drum switch. Thus, the sequence is: plug and cord leading into protection device, then the drum switch, and then the motor. Some motors have thermal overload protectors built in. I've been less than trusting of them since the only motor in my shop to have one was the lathe motor that burned out. I confess that only the more expensive motors in my shop are protected.

Before moving on to the next topic, a final reminder - always include a ground wire in all your circuits so that if a short develops, you aren't the ground.

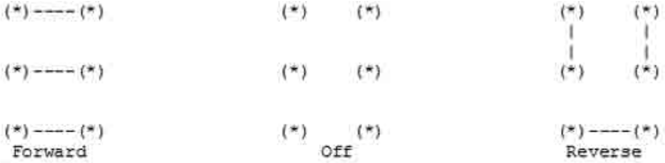
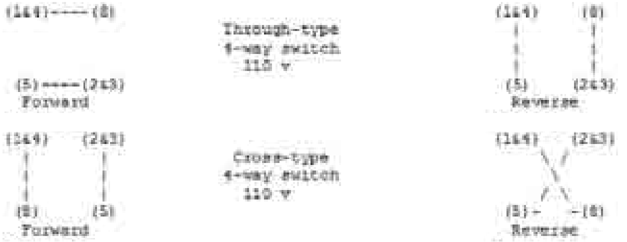


Figure 9



Figures 10, 11, 12 & 13

TROUBLESHOOTING

There are only a limited number of things that can go wrong electrically with split phase and capacitor motors. Listing what can go wrong is easy. Explaining how to isolate the circuits for testing can be difficult, and you'll have to use your own ingenuity plus the wiring schemes I've given you. You'll need an ohmmeter or a test lamp to do the testing.

If the motor doesn't even hum when you plug it in, it's either not getting any power at all or there's a break in one of the circuits inside the motor. Look at the windings. If one or more looks blackened and smells burnt, it's probably burned out. It doesn't seem profitable for motor repairmen to rewind small single-phase motors, so if you've burned out a winding, you're probably going to have to replace the motor.

If the motor hums but won't turn, there are several possibilities, all dealing with the starting windings. Check to see that all the connections are in the right place. Look for burned windings. Examine the capacitor. If it has leaked a few drops of oil, it’s no good.

Remove the wires to the capacitor and test it with an ohmmeter set on the 100x or 1000x scale. The needle should briefly swing toward 0 ohms and then drift back to the high end of the scale. If it doesn’t swing toward 0 ohms, short the capacitor with a screwdriver and try the test again; the capacitor may have had a small charge that would interfere with this test.

The centrifugal switch normally is closed and passes current when the motor is stopped. If it doesn’t, pull the bell ends off of the motor frame and look at the centrifugal switch contacts. Push the contacts together and test them with the ohmmeter to be certain they do or don’t transmit current. Oil or grease from the bearings can prevent the contacts from closing. Look at the contact surfaces for pitting or burning. If they need it, brighten them up with a point file or emery paper, taking care not to get the emery dust in the bearing.

If you don’t hear a click when the motor’s slowing down, the centrifugal switch isn’t working. Pull the bell ends off the frame and look at the centrifugal switch. The weights should be moveable although stiff because of spring tension. If the bearings are extremely worn, the rotor may touch the frame and prevent the motor from operating. I’ve never seen this, but I’d expect to find a lot of play in the motor shaft and either bright spots or burned spots inside the frame where the motor was rubbing.

If the motor starts but just doesn’t seem to have as much power as it should, look to see if one of the windings looks burned. Check to see that all the electrical connections are correct and clean. Make sure you don’t have the motor wired to run on 220v when you’re only using 110v.

ACHIEVING ENERGY EFFICIENCY AND MAINTAINING POWER QUALITY

Jeff Theisen, Senior Drive Application Engineer, Rockwell Automation

As recently as a few decades ago, manufacturers assumed that energy costs were simply uncontrollable. But such attitudes became outdated with the advent of variable speed drives and power-monitoring technologies capable of making energy a manageable expense – one that can be controlled by adjusting key processes to use less energy.

The ability to save energy today is considered a given in industrial settings, with tools and techniques to limit energy expenditures now including motor controllers, software and power monitoring and control devices capable of reducing energy costs and helping manufacturers control costs better than before.

Domestic manufacturers annually spend more than $33 billion on electricity, with motor systems consuming approximately 63 percent of all electricity. More than half of those motors are used in either fan or pump applications – key areas with phenomenal potential for energy savings. As a result, many manufacturers are looking for ways to reduce the power consumed for fan and pump applications.

FAN APPLICATIONS

As a rule, energy consumption in a fan or pump application varies by the motor's cube of speed, also called centrifugal load. For example, if the speed on a fan's motor can be decreased by half, the energy used to power the motor is actually decreased by 7/8. This equation, which also can be applied to pump applications, illustrates the point: (1/2)? = 1/8

Most fan applications do not require the full amount of air movement that fans are designed to produce. So, to vary airflow, fan applications use methods such as:

- cycling (generally used in residential settings and not applicable in industrial settings),
- outlet dampers,
- variable inlet vanes and
- variable-speed drives.

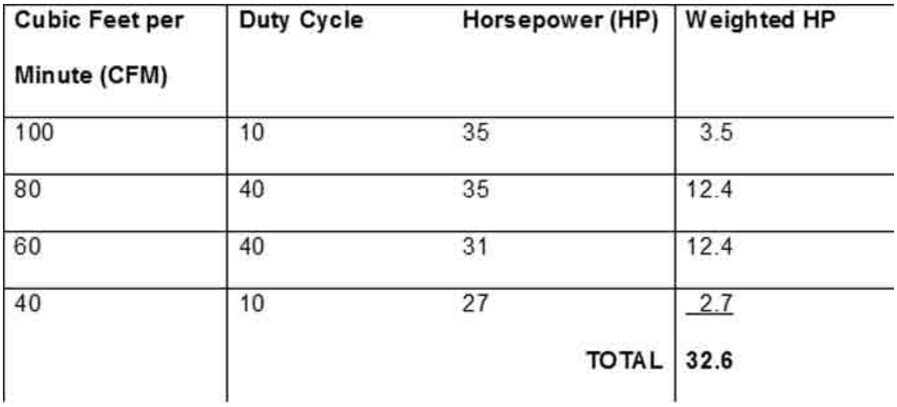
In industrial settings, variable speed drives are generally the most effective means of controlling energy use because they control actual motor speed. Methods such as inlet vanes and outlet dampers only control the amount of air an application receives, not motor speed.

Charts 1 and 2 show the actual amount of energy used when controlling air flow using either outlet dampers (Chart 1) or variable speed drives (Chart 2). The figure in the right-hand box, "weighted horsepower", calculates the average horsepower used during a fan's on/off cycle, including the power needed to ramp up to speed and slow down.

Weighted horsepower is important, because it provides a glimpse into the amount of energy each motor uses to control air flow. Estimating power consumption and potential energy savings requires an actual load profile and a fan curve, both of which will vary over the course of fan operation (since fans need to ramp up to speed before operating at desired capacity).

The weighted horsepower of a fan is calculated by the percent of time a fan operates at a given power point. Calculations are summed to produce the weighted horsepower that represents the fan's average energy consumption.

Chart 1: Outlet Dampers



Cubic Feet per Minute (CFM)	Duty Cycle	Horsepower (HP)	Weighted HP
100	10	35	3.5
80	40	35	12.4
60	40	31	12.4
40	10	27	2.7
		TOTAL	**32.6**

Similar calculations can provide weighted horsepower figures for variable speed operations. However, because the fan curve does not have enough information to read all horsepower values for operating points, formulas from affinity laws need to be incorporated into the calculation.

The first point is obtained from the fan curve: 100 percent flow equals 100 percent speed, which equals 35 HP. The flow formula Q2/Q1 = N2/N1 can be substituted into the horsepower formula, HP2/HP1 = (N2/N1)? to give:

When Q1 = 100 percent and HP1 = 35 HP, Q2 and HP2 have the following values:

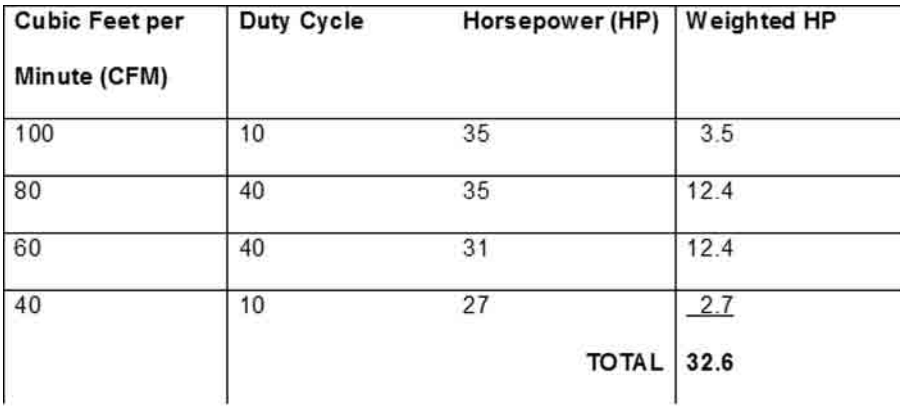
Example: (Q2/Q1)3 * HP1 = (80/100)3 * 35 = 17.92

Q2	80%	60%	40%
HP2	18	7.56	2.24

Sufficient information is now available to calculate weighted horsepower for variable speed operations.

In the examples outlined in Charts 1 and 2, we see that the outlet damper application has a weighted horsepower of 32.6, which is significantly higher than the variable speed drive's 13.948 weighted horsepower. In a hypothetical situation in which this same fan application is used 730 hours per month, with electricity costs averaging $0.07 per kWh, the dampered

Chart 2: Variable Speed Drives



Cubic Feet per Minute (CFM)	Duty Cycle	Horsepower (HP)	Weighted HP
100	10	35	3.5
80	40	35	12.4
60	40	31	12.4
40	10	27	2.7
		TOTAL	**32.6**

fan would incur more than $1,242 in energy costs. Meanwhile, the drive-controlled fan would use approximately $531 in electricity, representing a significant cost savings over the outlet damper system.

PUMP APPLICATIONS

Variable speed drives also can contribute to energy savings for pump applications. Controlling the speed of a pump is accomplished either through throttling the motor (mechanically changing the pump's speed) or employing a drive to control the motor's speed – and, therefore, the amount of energy used by the pump motor.

Just as certain calculations can show the energy savings possible in fan applications, similar calculations can be used to estimate energy savings for pumps. Generally, when pump speed is reduced by 20 percent from 100 percent, motor hp is reduced by nearly 50 percent, as is Brake HorsePower (BHP) — the indicator of how much energy a pump motor is using. BHP is equivalent to the power necessary to do the work at a particular speed divided by the motor efficiency.

For example, a motor/pump is running on a system across the line that flows 450GPM. However when the demand is only 225GPM, the flow is reduced by partially closing a valve. According to a pump curve, the pressure is increased from 180psf to 200psf, the efficiency is reduced from 76% to 60% and the horsepower requirement reduces from 30HP to 26HP. That same application on a variable speed drive would reduce the horsepower to 3.75.

Assuming a 225 GPM flow is required for 3000 hours a year at $0.07 per kWh, the comparison of costs for throttling versus a variable-speed drive system is dramatic:

Throttling:
26 HP x 0.746 = 19.396 kW
19.396 x 3000 = 58188 kWhr
58188 x $0.07 = $4073.16

Variable speed drive:
3.75 x 0.746 = 2.97 kW
2.97 x 3000 = 8392.5 kWh
8392.5 x 0.07 = $587.48

SAVINGS:

$4073.16 - $587.48 = $3485.68 saving in energy costs using variable speed drives

It's important to note that the above example assumes the pump system does not have a static head, or great resistance to flow, as is often associated with long pipes or pump length that rises significantly. The higher the resistance to flow, the lower the potential energy savings. Motor and drive efficiencies were also not considered.

In addition to taking advantage the Affinity Laws provide, additional benefits are relieving the stress on the mechanical system by not starting across the line vs. a drive ramping up to speed. Tighter process control can also be realized with the correct drive utilization.

HARMONICS AND POWER QUALITY

Power quality is an issue in all facilities that use large amounts of energy, including harmonics often associated with variable frequency drives.

Harmonics are deviations from the sinusoidal fundamental AC line voltage and current. While most electrical power in North America operates at a frequency of 60 hertz, a harmonic frequency operates at a multiple of its fundamental frequency. So, in a 60-hertz system, the second harmonic would be 120-hertz, the third would be 180-hertz and so on.

IEEE 519 ensures power quality by limiting the maximum current distortion caused by non-linear loads to limit the voltage distortion they would create, minimizing the likelihood of equipment failure due to the distortions. In other words, limiting the harmonics on electrical lines, both in and around facilities, improves power quality.

The addition of harmonics to the sinusoidal fundamental current or voltage creates distortion. The greater the amplitudes of harmonics present, the greater the distortion in the electrical waveform. What this means, very simply, is that whenever a voltage or current does not look like a perfect sinusoidal waveform, it contains harmonics.

Unlike an AC motor operating across the power line, the current drawn from a distribution transformer feeding a typical AC drive is far from a sinusoidal waveform. This occurs because the drive is taking current from the transformer only during certain times of the cycle to convert the AC line voltage to a fixed DC voltage within the drive. The drive then pulse-width modulates fixed DC voltage into variable frequency voltage for the motor. The AC-to-DC conversion is what causes the harmonics. Current flows only during part of the cycle and is off during other parts of the cycle, creating an odd-looking current waveform. The distorted current creates voltage distortion.

Several methods and products can reduce line current harmonics created by drives. Even though the addition of line reactors or passive filters can help reduce the current harmonics, in some conditions they also will reduce the DC bus voltage within the drive in full-speed, full-load conditions. This will prevent the drive from being able to provide full power to the motor, limiting the power out of the motor to about 95 percent of its nameplate rating. Why install a 100-HP motor only to have its capability limited to 95 HP, especially under peak demand conditions? This is why multi-pulse solutions are a better fit for most situations, since no de-rating is necessary and such solutions are generally less expensive than other mitigation methods.

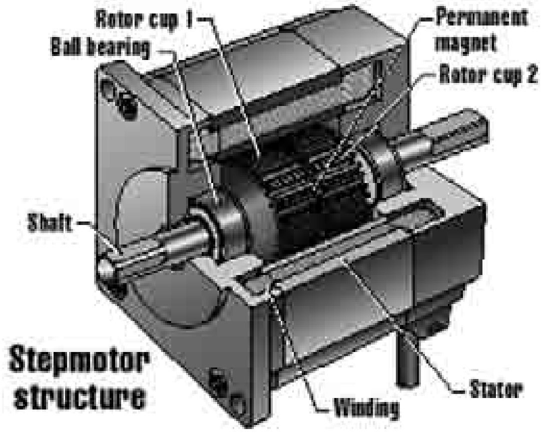
Manufacturers and users of industrial motors have more control over their energy costs today than they may realize. Likewise, power quality issues can also be mitigated with the technology that improves each year. Regenerative drives that put excess energy back on electric lines are available, and drives are being developed with more and more robust features, such as positioning capabilities. All of these features make drives an integral part of an energy savings program— far beyond the simple speed controllers they used to be.

RESOLUTION, VIBRATION, TORQUE, ACCURACY AND SYNCHRONISM ARE ALL FACTORS WHEN APPLYING TWO-AND FIVE-PHASE STEPMOTORS

Fernando da Rosa, Coordinator; Nick Johantgen, Engineer Manager; Craig Ludwic, Applications Engineering Manager, Oriental Motors USA Corp.

Technically, there are two key differences between two - and five-phase stepmotors or steppers. The first is mechanical, primarily in the construction of the stator. Rotors in both kinds of motors comprise two rotor cups and a permanent magnet. Spaced around most rotors are 50 teeth created by machining grooves into the rotor cups. The two-phase stator, though, has only eight magnetic pole pieces. The five-phase stator has 10 pole pieces. Windings of copper wire wrap around each pole piece.

The second difference between the two kinds of stepmotors is, obviously, the number of phases. In this context a phase refers to the different combinations of poles that energize in sequence to move the rotor. Two-phase steppers have only two phases labeled A and B. Each phase uses four poles arranged as two pole pairs. The first A-phase pole pair is labeled as A while the second pole pair is given the designation A'. Both pole pairs are energized when A-phase power is applied. The same arrangement of poles exists for the B phase.



This cutaway identifies the basic elements that make up a stepmotor. Each rotor cup has 50 teeth spaced 7.2° apart.

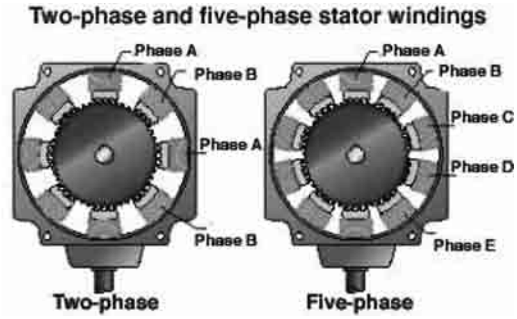
The five-phase stepmotor adds three more phases labeled C, D, and E. But, unlike the two-phase stepmotor, the five-phase motor uses only a single pole pair per phase.

It should be said that there are several ways to drive a stepmotor. The type of drive greatly affects motor performance. The most common drive methods are wave drive, full step, half step, and microstep. Each type has advantages and disadvantages, but those details are beyond the scope of this article. So this discussion will focus on the key areas of performance without accounting for drive type.

RESOLUTION AND VIBRATION

Structurally, five-phase steppers differ little from two-phase steppers. As stated, both have a rotor typically with 50 teeth. But the five-phase stepper has 10 poles, two per phase. The rotor need move only 0.1 of a tooth to line up with the next phase. In contrast, the two-phase stepper with its four poles per phase has to move 0.25 of a tooth.

This gives the two-phase 200 steps/rotation or 1.8°/step, while the five-phase has 500 steps/rotation at 0.72°/step. The higher resolution of the five-phase stepper motor is built into its design. Typical mechanical accuracy for both two-and five-phase motors is ±3 arc min or ±0.05°.



The principal difference between a two-and five-phase stepmotor is in the number of poles and phases/pole. The two-phase stepmotor contains eight stator poles at four poles/phase. The five-phase stepmotor contains 10 poles, but only has two poles/phase.

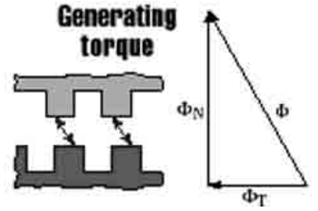
The smaller step angles in five-phase stepmotors gives them about one-tenth the vibration of a two-phase stepper at lower frequencies.

TORQUE

There is little difference between the output torque of two-or five-phase stepmotors. But five-phase steppers have more usable torque. It's the amount of torque ripple both motors produce that accounts for the difference.

Torque ripple comes from rotor movement. When the stator is energized, it becomes an electromagnet, which attracts the magnetic flux of the rotor. The magnetic flux divides into two vectors, one direct and one tangential. The tangential component is the only one that produces torque as the magnetic flux pulls the rotor towards it.

Each phase of the motor contributes a sine-shaped displacement curve to the total output torque of the stepper. The difference between the peak and valley is the torque ripple. Torque ripple contributes to motor vibration. The greater the difference between peak and valley, the greater the vibration.



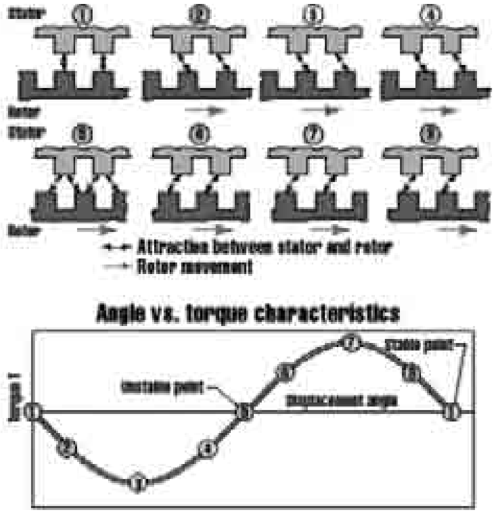
Stepper motors create torque when the rotor is out of alignment with the stator. The magnetic force creates two magnetic force components: a neutral force N which is ignored, and a torquing force, T. The amount of torque is controlled by the strength of the magnetic field and the angle between the rotor and stator slots.

A five-phase stepper has less ripple because there are more phases contributing to the total torque. There can be as much as a 29% difference between peaks and valleys in a two-phase stepmotor. In comparison, a five-phase stepmotor only creates about a 5% difference and thus runs more smoothly.

ACCURACY AND REPEATABILITY

Stepmotor accuracy has two components: one mechanical and the other electrical. Electrical errors come from out-of-balance phases. For example, the motor winding resistance has a spec of ±10%. If the motor is nominally rated at 10Ω one phase could be only 9.2Ω and the other 10.6Ω and still meet design spec. But the difference in current through each winding would make the rotor align more towards the stronger magnetic field.

A major cause of mechanical error is tooth configuration. Though the teeth on a motor should be square, the stamping process and age of the die can round the edges on some of the teeth. The round edges cause magnetic leakage that creates an offset magnetic field rather than one straight-on dead center.



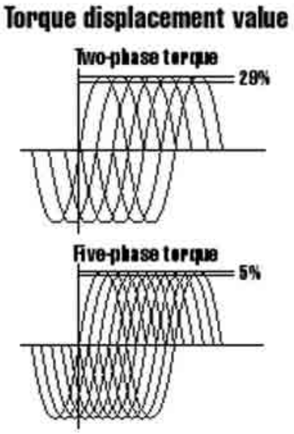
At point 1, the rotor teeth directly line up with the stator teeth; the magnetic flux has only a normal component directly from the pole to the rotor. No torque is produced. As the rotor teeth displace from the stator teeth at points 2, 3, and 4, the motor produces torque. This torque is considered negative because it is trying to pull the teeth back into the stable position. At point 5 the flux splits evenly between the stator teeth and no torque is produced. Points 6, 7, and 8 produce a positive torque as the displaced rotor teeth move to line up with the next set of stator teeth. When the rotor teeth reach alignment with the stator teeth, the stepmotor is back to point 1.

Using full-step drives, a two-phase stepper repeats states every fourth step while a five-phase stepper repeats every 10 steps. Electrical errors caused by unbalanced phases are eliminated every fourth step in a two-phase stepper and every tenth step in a five phase, leaving only mechanical errors. On the other hand, mechanical errors begin repeating every revolution. At 200 and 500 steps, respectively, the alignment is nearly perfect with the starting point and the cycle repeats.

SYNCHRONISM

Synchronism refers to how well a stepmotor remains in alignment or synchronized with the controller. Many stepmotor controls run open loop. They determine position by counting the number of steps in the direction of rotation. Each step corresponds to a specific length of travel or rotation. If the motor is asked to step faster than its inertia lets it move, it will miss a step as the proper teeth fail to line up. There is alignment to the tooth next to the proper tooth, creating a rotation error of 7.2°.

Recognizing there are 50 teeth on a stepmotor rotor, each tooth is 7.2° apart. If the rotor overshoots or undershoots the correct stator tooth by more than 3.6°, the next tooth on the rotor will align in its place. A two-phase stepmotor moves 1.8°/step. So a two-phase stepper need only miss two step commands to lose synchronism. Conversely, a five-phase stepper must miss five step commands to lose synchronism.



The torque generated by each stator pole varies from the peak to the bottom of the valley between the peaks. Because of the smaller number of two-phase stator poles, the torque value changes 29% between maximum and minimum values compared to only 5% for the five-phase stepmotor. Though both motors generate the same maximum torque value, the smaller variation in the five-phase stepmotor produces more effective torque with less noise and vibration.

All in all, five-phase stepmotors offer higher resolution, lower vibrations, faster acceleration and deceleration, and are less likely to lose synchronism.

EFFICIENCY OPPORTUNITIES THROUGH MOTOR MAINTENANCE

Peter A. Darbee, Pacific Gas and Electric Company

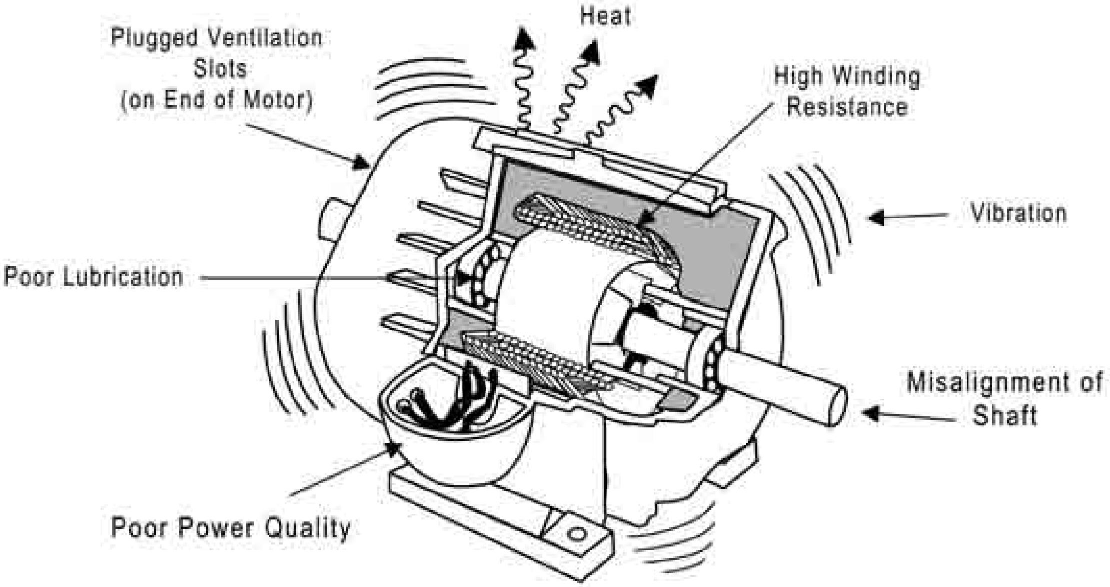


Figure 1: Sources of Potential Motor Efficiency Losses that can be Avoided with Proper Maintenance

The electricity consumed by a motor in one year costs more than the motor itself, by as much as 10 times. Multiplying this cost by the life of the motor puts the necessity of maintaining optimum motor performance in true perspective.

Motor maintenance is more than making sure the motor itself is operating correctly.

It also involves ensuring that power supplied to the motor is within acceptable tolerances, that the motor's output power is efficiently transmitted to the load and that the load itself is properly maintained so as not to make the motor work harder than necessary.

Record keeping is an essential part of motor maintenance. Comparing results of recent tests to historical records, maintenance staff can much more readily spot degraded performance and potential breakdowns and take steps to adjust the system and avoid costly unscheduled downtime.

Motor maintenance programs must be customized. Hot, dirty, humid conditions require more frequent checks of performance and attention to maintaining the physical condition of the motor. It may also be necessary to isolate motors from extreme conditions or to blow conditioned air over them for cooling purposes.

HOW MOTOR MAINTENANCE SAVES ENERGY

Motors eventually become less efficient through wear, breakdown of lubricants and falling out of alignment. Scheduled maintenance is the best way to keep the whole system operating within acceptable tolerances. Properly applied, maintenance will also provide valuable information on potential motor failure so that unscheduled downtime can be minimized. Potential sources of efficiency loss are shown in Figure 1.

MOTOR MAINTENANCE ENERGY-SAVING STRATEGIES

The greatest enemies of efficient motor operation are improper installation or adjustments, low-quality electrical power, adverse environmental conditions (e.g., dust, dirt, moisture, extreme temperature) and wear. The general guidelines in this section address these issues.

MOTOR MAINTENANCE LOGS

A motor maintenance program is of most value when it is consistently applied.

The system should remind staff when it is time to perform specific maintenance functions on individual motors; provide a means of recording the functions performed; and act as an historical record to track the performance of individual motors.

Each motor should have a maintenance form, recording the load served (e.g. supply fan #1 or boiler feedwater pump #3) and the motor's make, model, serial number and ratings. Specifications for ancillary equipment (e.g., drive belts, pulleys) should be recorded for quick reference. Space should be provided for recording observations of unusual motor performance.

Computerized maintenance programs are available that will notify plant personnel of upcoming motor maintenance.

These programs also provide a convenient repository for information on all motors (plus other systems that require maintenance) and analysis tools for determining how effectively maintenance is being carried out.

PROPER LUBRICATION

Proper lubrication is essential to long operating life for motors and all mechanical equipment. It must be done periodically and consistently — it is too late when the motor audibly communicates its needs. Many times service personnel try to quiet a noisy motor by pumping lubricant into the bearing. This may work for a short while but the life of a noisy bearing is limited and over-lubrication (as described below) may result.

Too much lubrication can be just as harmful as too little. Excess oil or grease tends to accumulate: Windings become coated and this film collects even more dirt, moisture and, if brushes are involved, carbon dust. Oil and grease on the stationary switch contacts may cause them to overheat, arc or burn, and even to weld themselves closed. Lubricants harm many internal motor parts. If the manufacturer has lubricant recommendations, they should be followed, especially in severe duty applications.

SHAFT ALIGNMENT

Larger motors are usually coupled to their loads and proper shaft alignment is important to adequate bearing life. In belt-driven applications, belts must be perpendicular to the shaft axes or they will wear and bearing life will be shortened.

Alignments made under one set of circumstances can change due to temperature, loading, foundation movement and rotational speeds.

Motor output power is transferred to the load by belts, chains, gears or direct couplings. Belt drives depend on pulleys, or sheaves, mounted on the shafts of the motor and the load. A continuous belt wraps around the sheaves and, as the motor sheave turns, power is transmitted to the load. Chain drives work in a similar manner, but the belt is replaced by a chain and sheaves are replaced with cogged sprocket wheels, similar to a bicycle chain and sprocket.

Gear drives can be used to greatly increase or decrease the rotational speed of the load and to reverse its direction, depending on the sizes, number and arrangement of gears used. Direct couplings make a semi-permanent connection between motor and load shafts that are aligned end-to-end and may be categorized as rigid, flexible or fluid.

In direct-coupled drives, proper alignment exists when a straight line through the motor shaft axis extends through the axis of the driven equipment shaft.

Flexible couplings can, to some extent, make up for improper alignment.

An exaggeration of a typical direct-coupling misalignment situation is shown in Figure 2 which contains both radial and angular errors. The object is to make distances A1 and A2 between the coupling faces equal, and to reduce distance R between the coupling rims to zero.

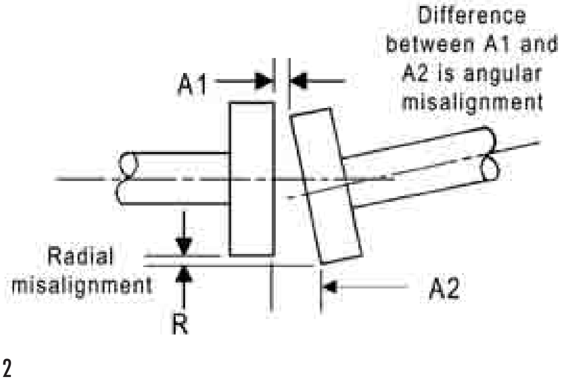


Figure 2

BELTS AND PULLEYS

Pulleys also need to be precisely aligned for optimum performance. They must also be properly spaced for belts to have the right tension. Figure 3 illustrates both parallel and angular misalignment; either will result in unnecessary friction between belt and pulley.

Belt tension is achieved by moving the pulleys. If they are too far apart, undue stress is placed on the bearings of the pulley shaft, shortening their life. If too close together, the belt will slip on the pulleys, losing efficiency and wearing excessively.

BELTS AND PULLEYS MUST BE KEPT CLEAN

Dirt, oil or grease on either can lead to shortened belt life and inefficient transfer of power. If needed, belts should be cleaned with a rag dampened with a light, non-volatile solvent. Belts should not be soaked or brushed with solvent and they should not be sanded or scraped.

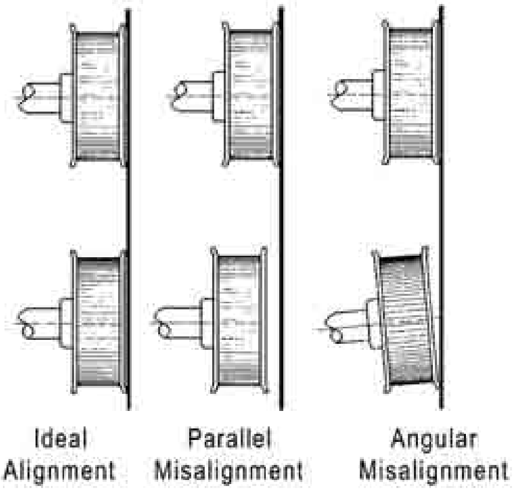


Figure 3: Typical misalignments of sheaves

BEARING MAINTENANCE

All bearings require maintenance to perform properly and achieve their service lives. Bearings can be classified as sleeve or anti-friction types. In sleeve bearings, the shaft rides in a thin film of lubricant between the shaft and the bearing. Anti-friction bearings have ball or roller bearings that spin between the shaft and the bearing housing. There is considerable overlapping in the use of both types in electric motors. Proper maintenance consists simply of keeping the bearing clean, lubricated and loaded not in excess of its rating.

COMMUTATOR MAINTENANCE

The commutator is a vital part of every DC motor. Fortunately, commutators tend to show signs of distress in advance of serious trouble. Periodic inspection is a valuable preventive maintenance tool.

Brushes must maintain good physical and electrical contact with the commutator surface. If surface irregularities or rotational speed cause the brushes to lose contact, arcing, burning and flat spots can occur. In extreme cases, the leading edges of brushes may be shattered.

Besides mechanical surface considerations, the proper surface film must be developed and maintained. This film is the result of electrochemical deposition of carbon, graphite, copper oxide and water vapor on the commutator surface.

Brush and commutator wear will be accelerated if this film is damaged mechanically, electrically, or chemically, or is contaminated by dirt. A smooth, even, glossy copper, brown, or chocolate color is normal. Sometimes a color pattern may be evident between bars; as long as the pattern is repeated around the entire commutator, there is no cause for concern.

Regular inspection will reveal developing problems. If problems are noted, the commutator should be removed and turned on a lathe to remove any flat spots and ensure concentricity. Brushes should also be replaced during reassembly.

POWER QUALITY

Power quality can have a large impact on motor performance. Motors are designed with the assumption that electric power will be provided within certain tolerances.

It is easy to assume that because motors are operating, the power is within acceptable tolerances, but this is not always true. Power quality can be degraded as it is supplied from the utility or at the facility; in either case, it is necessary to identify the cause and correct it. Important power quality issues are discussed below.

SINGLE-PHASING

This occurs when one leg of the three-phase supply system opens. It could be caused by a utility failure, a broken circuit in the plant, a bad contact in the motor starter or a single blown fuse.

Three-phase motors subjected to single-phasing while carrying a substantial load will continue the attempt to drive their loads, while drawing elevated currents on the remaining two lines. Unless removed from service, they will experience winding damage: Inspection will show a repeated pattern of burning in the end-turn region; windings connected to the phase that was de-energized will appear undamaged. Ampere readings taken on each leg will show two legs at high current levels will carry no current.

UNBALANCED VOLTAGE OPERATION

This condition is recognized in the industry standards. All polyphase motors can operate successfully when the unbalance at the motor terminals does not exceed 1 percent. Voltages, preferably, should be evenly balanced as closely as can be read on a voltmeter. In actual practice, there is always some degree of unbalance. For example, you might obtain three line-to-line voltage readings of 233, 230 and 228 volts. The formula for calculating percent unbalance is:

$$\%\_unbalance = 100 \times \frac{max\_deviation\_from\_avg\_voltage}{avg\_voltage}$$

It is not recommended that motors be operated with an unbalance condition of more than 5 percent, which carries a recommended motor derating to 75 percent of rated horsepower according to NEMA Standard MG1-14.34. Corrective action should be considered when voltage unbalance exceeds 1 percent. Heat generated by a 2 percent unbalance may reduce insulation life 8 times.

Measurement of the three line-to-line voltages at the service entrance will indicate if voltage unbalance originates with the utility. Usually the problem is internal and caused by an unequal distribution of single-phase loads between the phases. Correction requires redistributing the single-phase loads between phases to produce a balanced supply to all motors affected.

VOLTAGE AND FREQUENCY

Permissible limits for voltage and frequency are also defined by NEMA. Both AC and DC motors will operate satisfactorily over a range of 10 percent of rated voltage and universal motors over a range of 6 percent of rated voltage.

The standards also permit a frequency variation of 5 percent of rated frequency.

A combined variation in both voltage and frequency of 10 percent (sum of absolute values) is permitted, provided the frequency variation is not more than 5 percent and the voltage variation for universal motors does not exceed 6 percent (except for fan motors).

The turning force produced by a motor (i.e., its torque) is proportional to the square of the applied voltage. For example, if the voltage applied to a motor is 80 percent of the motor's design voltage, it will only produce approximately 64 percent of it rated torque. High efficiency motors are less affected than standard motors.

MOTOR CIRCUIT ANALYSIS

An advance in motor testing has evolved as a powerful tool for assessing and maintaining motors and the electric circuits that feed them. The technology, generally called motor circuit analysis (MCA), measures the absolute and relative resistance, inductance, and capacitance of motor circuits and windings.

An historical record of such testing lets the operator assess the integrity and failure risk of individual motors.

Consistently applied, MCA can help avoid motor failures, enable proactive maintenance or replacement, and improve the energy efficiency of motor systems in general.

What makes MCA unique is the grouping and automation of powerful testing methods it includes. Because all test data are acquired by a common system and the various tests are nearly simultaneous, MCA offers much better assessments of motor integrity.

MCA is still an evolving technology, but at least five manufacturers offer MCA equipment and testing services. Several dozen industrial companies are using the technology and report encouraging results in reduced downtime, increased production, and improved energy efficiency.

More traditional analytic methods involve measurements of winding resistance.

Insulation electrically isolates the windings from the grounded frame, one conductor from another and one phase from another. They are subject to electrical, mechanical and thermal stresses and the effects of external contamination and moisture. The service life of a motor will largely depend on the level of care given its insulation. The maintenance program to be followed depends on the operator's experience and philosophy.

The records of tests performed on a motor can be extremely useful in evaluating its present insulation condition.

Motor windings are factory-tested, but in spite of this testing, motors have a higher failure rate immediately after installation.

Once the "infant mortality" phase has passed, the failure rate will be lower until the effects of service and aging begin to take hold.

In the field, low-voltage tests are generally used to determine insulation condition.

This may be the only test required or it may be the necessary initial test prior to high-voltage testing. This testing is referred to as "megger" testing after the piece of equipment used. Acceptable values of insulation resistance must not be less than 1 megohm per kV of motor rating (rounded up) plus 1 megohm when testing is performed at 104°F. For example, a 600 volt motor is rated at 0.6 kV, so minimum insulation resistance would be 0.6 + 1 megohms rounded up to 2 megohms. Insulation resistance doubles for each 18°F reduction in temperature (above the dew point) and corrections should be applied to tests made at other than 104°F winding temperatures. If the 600 volt motor was tested at 86°F, the minimum resistance would be 2 x 1.6, or 3.2 megohms, rounded up to 4 megohms and tests performed at 68°F would require a minimum resistance of 2 x 3.2, or 6.4 megohms rounded up to 7 megohms.

Larger motors have more insulation surface, thus lower insulation resistance.

Motors as large as the 680 frame size should have insulation resistances above 50 megohms if clean and dry and the insulation is not deteriorated. Small motors with healthy insulation may register close to infinity on the megger scale.

Keeping records of past measurements is very important. Consider, for example, two motors both testing at 18 megohms. Motor A has an historical insulation resistance level of 120 megohms; clearly its insulative value has significantly deteriorated and thorough cleaning and/or drying is called for before placing it in service. Motor B, on the other hand, has an historical figure of 20 megohms and can be placed in service with little cause for concern.

Dielectric absorption tests provide additional valuable information, especially for higher voltage motors with form-wound coils. This method requires the determination of insulation resistance after one minute and again after 10 minutes of megger voltage application.

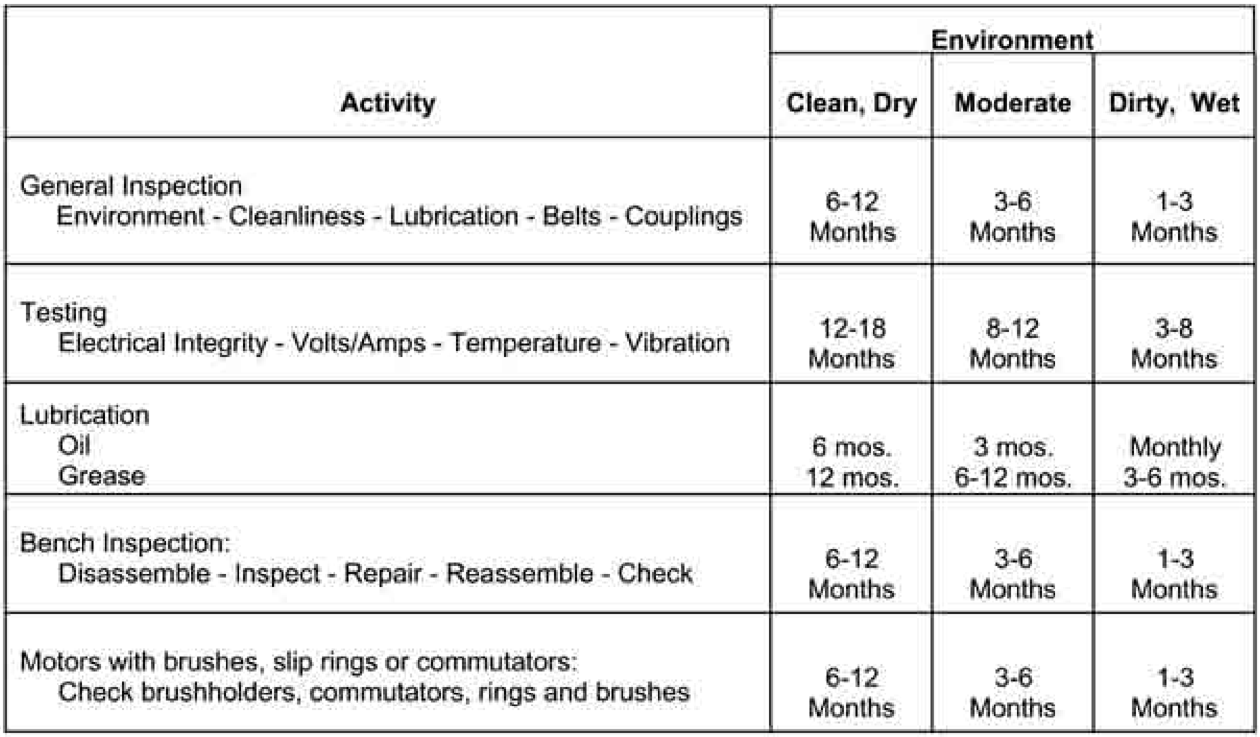
The 10-minute value divided by the one-minute value is called the polarization index. The recommended minimum value for AC and DC motors is 1.5 for Class A insulation and 2.0 for Classes B and F insulation.

These tests are considered more meaningful than one-minute megger tests. Low values generally indicate moist or contaminated windings which require drying out or cleaning. The motor can be disassembled and the windings cleaned with an approved solvent compatible with the insulation system.

Dirt can be flushed from windings and cooling passages with water, but careful drying will have to be performed. Windings are normally dried either in baking ovens at 175 - 195°F, by blowing warm, dry air over them, or by passing current through them to generate internal heat.

This process can take several days and periodic testing should be performed to track progress. For more information on insulation testing and maintenance, refer to IEEE Standards 43 and 432.

Table 1: Approximate frequency of motor O&M procedures



Activity	Environment		
	Clean, Dry	Moderate	Dirty, Wet
General Inspection Environment - Cleanliness - Lubrication - Belts - Couplings	6-12 Months	3-6 Months	1-3 Months
Testing Electrical Integrity - Volts/Amps - Temperature - Vibration	12-18 Months	8-12 Months	3-8 Months
Lubrication Oil Grease	 6 mos. 12 mos.	 3 mos. 6-12 mos.	 Monthly 3-6 mos.
Bench Inspection: Disassemble - Inspect - Repair - Reassemble - Check	6-12 Months	3-6 Months	1-3 Months
Motors with brushes, slip rings or commutators: Check brushholders, commutators, rings and brushes	6-12 Months	3-6 Months	1-3 Months

APPLICABILITY

Motor maintenance is applicable to all motors without exception. Because the cost of energy to operate a motor over its life far exceeds its original cost, it makes sense to minimize energy costs by maintaining motor systems at close to optimum efficiency. Table 1 provides general guidelines on the frequency of inspections and testing.

FIELD OBSERVATIONS TO IDENTIFY MOTOR INEFFICIENCIES

This section discusses field observations and checks to ensure that motor maintenance practices are sufficient for efficient system operation.

RELATED TO APPLICABILITY

- The environment in which motors operate is the most obvious indicator of the level of maintenance required. Dirty, dusty, humid or hot environments indicate the need for more frequent maintenance.
- Motor temperature has traditionally been used as a rough indication of motor efficiency — inefficient motors have greater losses manifested as heat, which leads to a hotter motor. This test is not as reliable as it once was due to better insulation performance. Table 2 gives maximum temperature and ranges of operating temperatures for existing winding insulation classes. Note that these are winding temperatures; the motor housing temperature will be lower. It is best to use a contact thermometer on the motor housing and record the readings for ongoing maintenance procedures.
- Excessive vibration indicates that some part of the motor system is out of balance and needs attention. The imbalance may be in the alignment of the drive, it may originate with the load, or it may be due to worn or out-of-balance motor parts.
- Excessive noise is another indication of a problem with the system.

These problems can arise from worn parts (e.g., bearings), broken parts within the motor, squealing of loose belts, chatter from misaligned drives and a number of other sources.

- Starting and stopping a motor stresses all its parts, and this can degrade performance. The more frequently it is stopped and started, the more frequent maintenance should be.

RELATED TO ENERGY SAVINGS

- Motors hot to the touch are usually dissipating energy as heat. An efficiently operating motor converts at least some of this wasted energy directly from electric to mechanical energy (i.e., to turn the motor shaft). Thermographs can be very helpful in identifying trouble spots.
- Loud or vibrating motors or loads indicate a problem that should be resolved.

Energy losses associated with noises and vibrations may not be great, but may indicate problems such as worn bearings, improper belt tension or broken parts, any of which will have some impact on energy performance.

- A build-up of dirt, dust, grease or other contaminants indicates the motor is probably not getting adequate cooling, which will result in inefficient operation.

RELATED TO IMPLEMENTATION COST

- The cost of an effective electric motor O&M program will be influenced by the number of motors and their sizes.
- Motors with difficult access will require more labor effort to maintain.
- Motors in dusty, dirty or humid environments may require regular inspections as much as six times as often as motors in clean environments.

Loads that tend to vibrate may require increased attention to alignment and tension.

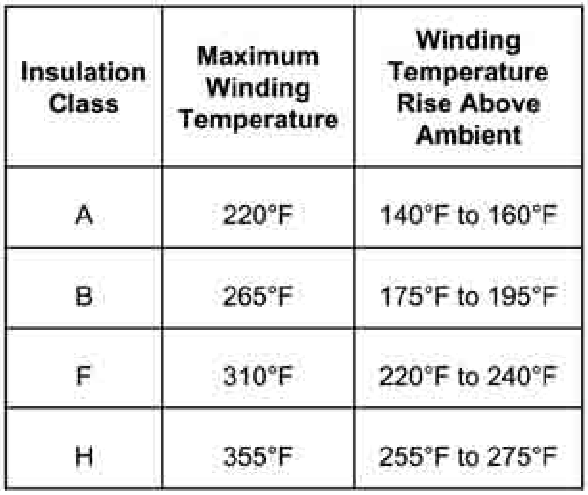
ESTIMATION OF ENERGY SAVINGS

Energy savings realized from motor maintenance come from maintaining optimum efficiency and are really avoided consumption, as opposed to energy reductions.

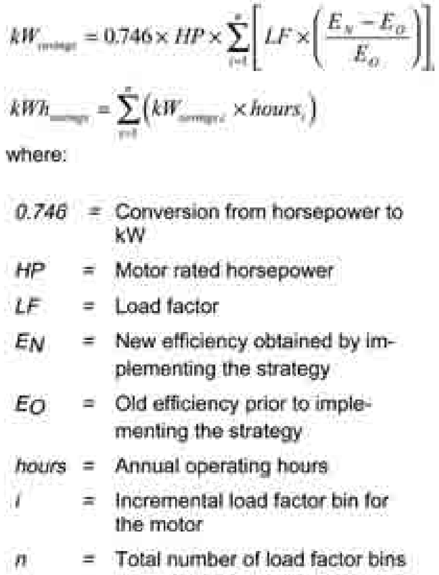
An accurate estimate of savings would require determining what would be consumed if good maintenance were not practiced. This value is difficult to quantify. The following equations provide a method for determining demand reduction and energy savings.

If the motor experiences a variable load, the range of

Table 2: Approximate motor winding maximum operating temperature and temperature rise



Insulation Class	Maximum Winding Temperature	Winding Temperature Rise Above Ambient
A	220°F	140°F to 160°F
B	265°F	175°F to 195°F
F	310°F	220°F to 240°F
H	355°F	255°F to 275°F



$$kW_{savings} = 0.746 \times HP \times \sum_{i=1}^{n}\left[LF \times \left(\frac{E_N - E_O}{E_O}\right)\right]$$

$$kWh_{savings} = \sum_{i=1}^{n}\left(kW_{savings,i} \times hours_i\right)$$

where:

0.746 = Conversion from horsepower to kW
HP = Motor rated horsepower
LF = Load factor
E_N = New efficiency obtained by implementing the strategy
E_O = Old efficiency prior to implementing the strategy
hours = Annual operating hours
i = Incremental load factor bin for the motor
n = Total number of load factor bins

loads should be divided into bins, or ranges of operation (signified by i in the equation above) and calculations made for each of those ranges, then summed. For example, the entire load range may be divided into bins representing decades of fractional load factors (i.e., 0 to 0.10, 0.10+ to 0.20, 0.20+ to 0.30, etc.) and representative values of load factor, efficiencies and hours would be inserted in the equation for each bin. Note that for motors under steady load, this equation is simplified as there is then only one operating range for the motor.

In actual application, it is often necessary to estimate the hours of operation in each load factor operating range.

Similarly, efficiencies for each range may have to be obtained from plots or charts of typical motor data.

According to EPRI, "The efficiencies of mechanical equipment in general can be increased typically 10 to 15 percent by proper maintenance". This reduction in energy consumption is difficult to quantify as it is an avoided, rather than a reduced, consumption. The only way to determine savings would be to establish a baseline condition by stopping maintenance functions, which is clearly unacceptable.

FACTORS AFFECTING MOTOR MAINTENANCE COSTS

Motor maintenance costs will be influenced by ongoing costs such as: testing, inspecting, cleaning and drying; parts for repairs; consumables (e.g., lubricants, belts, etc.); and labor. Costs will be increased directly as the frequency of maintenance activities is increased. In addition, one-time costs may be incurred from time to time to correct problems associated with power supplied to the motors.

The level of testing performed on motors determines the cost of such testing.

These tests can be as simple as having maintenance personnel take voltage and current draw measurements, or as sophisticated as comprehensive motor circuit analysis tests. Actual costs for testing and repairs should be obtained from providers of these services.

If the motor is in a particularly dirty or hot location, it will require as much as six times as much attention. It is essential that motors be selected based on the environment in which they will be operating. It may also be desirable to isolate the motor from the environment with barriers or filters and cooling air in order for the motor to operate within design limits.

LAWS, CODES, AND REGULATIONS

The National Electrical Code (NEC) and Underwriter's Laboratories (UL) standards provide minimum requirements for the safe installation of electrical equipment. In addition, NEMA provides standards relating to motor ratings and procedures to be followed in rebuilding and repairing motors to ensure adequate performance and safety.

DEFINITIONS OF KEY TERMS

- Brushes: Stationary carbon blocks connected to the power supply of a DC motor. Electric current passes through the brushes to the commutator.
- Commutators: Sliding electrical contacts between the rotating armature and the stationary brushes connected to the external power supply in DC motors. The action of the electrical current on the commutator provides the force to turn the motor.
- Rotor: The center part of a motor which, in most designs, is attached to the output shaft and rotates.
- Stator: The fixed outer portion of a motor that surrounds the spinning rotor.
- Windings: In motor stators, the winding is a number of turns of insulated wire, usually copper, wrapped around a core of steel laminations.

MOTOR RELIABILITY REQUIRES A COMPREHENSIVE TESTING AND INSPECTION PROGRAM

James Piper, Maintenance Solutions

The electric motor is an essential element in many systems supporting facilities operations. Failures of electric motors in those systems can lead to inconvenienced building occupants, prolonged outages of services, and damage to the building and its contents. So, it is fortunate that most electric motors have a long, trouble-free service life, requiring only minimum maintenance to keep them operating.

But while a typical building electric motor might be a low-maintenance item, it still requires regular maintenance if it is to achieve the longest possible service life. The fact that most motors do not reach their design life is an indication that few organizations are properly maintaining their inventory of motors.

Establishing a motor maintenance program starts with an understanding of the causes of motor failure and the steps that can be taken to reduce their impact. It includes a program of regular inspections and maintenance activities, designed to keep motors running efficiently. And, it includes predictive maintenance activities to help identify and correct small deficiencies before they cause costly motor failures.

CAUSES OF FAILURES

Most motor failures can be attributed to five factors; heat, dirt, moisture, vibrations, and voltage irregularities. By focusing on eliminating or reducing a motor's exposure to these factors, a maintenance program can significantly reduce the rate at which motors fail, in the long run reducing maintenance costs and limiting interruptions for building occupants.

HEAT

Heat is the most common cause of motor failure before reaching rated service life. Every increase of 10 degrees Centigrade of a motor's windings above its design operating temperature cuts the life of the motor's winding insulation by 50 percent, even if the overheating was only temporary.

Overheating arises from a number of factors. If a motor is undersized for an application, or if a manager selects a motor with the wrong starting current and torque characteristics, it will operate warmer than its design temperature. Managers should always match all motors to their connected loads. While undersizing leads to overheating, oversizing lowers the application's energy efficiency.

Another common cause of overheating is operating the motor in an environment with a high ambient temperature, which reduces the rate at which heat can be conducted from the motor. This condition results in higher-than-rated winding temperatures and shortened service lives. Locating motors in inadequately ventilated areas or close to heat-producing equipment can easily result in ambient temperatures high enough to cause damage. Technicians should monitor the temperature in areas where motors are installed, adding forced ventilation if temperatures exceed the ratings for a motor.

Even if the ambient temperature is within the manufacturer's guidelines, plugged air passages, blocked cooling fans, and dirty cooling vanes will result in elevated motor operating temperatures. Managers should make sure technicians inspect motors at least annually to ensure that their cooling components are clear.

DIRT

Dirt is particularly damaging to mechanical and electrical motor components. It can accumulate on the surface of a motor, blocking its cooling vanes and fan, raising its operating temperature. Or, it can be drawn into the motor, where it abrades insulation, shafts and bearings. If dirt settles on a motor's windings, it can imbed itself into the winding insulation, reducing its insulating value and leading to possible insulation failure.

Unfortunately, the environment in which most building motors must operate, such as in mechanical rooms, is rather dirty. Cleanliness in areas that are not generally accessed by building occupants traditionally has been a low priority. But if motors are expected to perform over their rated service lives, then areas housing motors must be kept as clean as possible. Besides keeping debris from accumulating on floors and equipment, managers should make sure air intakes to these areas are screened and filtered if possible. If an area is exposed to high levels of dirt that cannot be controlled, motors should be protected with shielding devices.

MOISTURE

Like dirt, moisture attacks both the mechanical and electrical components in a motor. It corrodes the shafts, bearings, rotors, stator laminations and housings. It can penetrate the insulation of a motor's windings, leading to insulation failure.

While moisture is detrimental to the service life of any motor, it is particularly damaging in applications where a motor serves in a standby mode or is used seasonally. Unlike applications where motors operate continuously, intermittent applications might not generate sufficient heat within the motor to drive off the moisture.

Technicians should inspect all motor installations to ensure they are dry. If humidity levels are high, managers should consider using forced ventilation or mechanical dehumidification.

VIBRATION

Vibration in motors and the loads they drive can have a range of causes, some within the motor itself and some within the load that it drives. Vibration can result from:

- misalignment of the motor and load, which can cause shafts and couplings to flex and vibrate;
- loose motor or load mountings;
- unbalanced motor or load components;
- worn bearings, which can allow shafts to move off center;
- the accumulation of corrosion, grease or other debris on rotating components.

Over time, vibrations can destroy a motor's bearings or result in the formation of fatigue cracks in the insulation on the motor's windings.

Technicians should check motor alignment annually. Whenever they service a motor or its load, they should check it for proper balance. Once each year, they also should check motor- and load-mounting bolts for proper tightness. Each time they inspect a motor, they should be sure it is free from the accumulation of debris on rotating surfaces.

VOLTAGE IRREGULARITIES

While managers and technicians focus much of their attention on physical conditions that cause motor failure, they often overlook the quality and condition of the power source driving the motor. Any variation in the power beyond the level at which a motor is designed to operate can prove to be deadly to the motor. Undervoltage and overvoltage conditions cause rapid heating in the windings, shortening their life. Voltage spikes caused by lightning strikes and power switching can trigger failures in the winding insulation. And harmonics introduced by equipment located elsewhere in the facility can contribute to overheating of the windings.

For three-phase motors, an even more serious condition results from unbalanced voltage conditions. Even minor variations in voltages between phases will result in increased current flow and overheating of the motor's windings.

Once each year, technicians should check the voltage and current to all motors. If they suspect power problems, managers should consider installing monitoring equipment that can detect voltage spikes and system harmonics. Both conditions are best eliminated at their source, rather than at the motor. If they cannot be eliminated, technicians will have to add protective devices.

MOTOR MAINTENANCE

Maintenance programs for electric motors must start with an inventory of motors installed in a facility. But the inventory should go beyond just a simple listing of motors installed, their locations and the loads they power. The inventory also must examine the characteristics of the application as a way of determining if a motor that is installed is the correct type and rating for that application. If a motor and load are mismatched, even the most thorough maintenance program will not be able to prevent motor failures.

Given the number of motors found in most facilities, managers will have to prioritize the inventory. It is doubtful that any facility would have the resources required to implement a comprehensive maintenance program on all its motors. Instead, managers should identify motors that, if they failed, would create a threat to the safety and security of a facility and its occupants, a major disruption to operations, or a significant economic loss to facility owners.

At a minimum, managers should implement routine and preventive measures for those motors. Annual inspections, record keeping, vibration testing, cleaning, voltage and current readings, and lubrication all will help to keep a motor operating. But preventive measures alone cannot prevent or even minimize motor failures. Motors still will fail, seemingly without warning.

Motors, however, do give warnings of impending failures that technicians can identify by using several predictive maintenance procedures, including insulation resistance testing, polarized index testing, and DC high-potential testing. By tracking the results of these tests over time, technicians can identify trends of deterioration.

The insulation resistance test is one of the oldest predictive tests used to evaluate the condition of a motor's insulation. A megohmmeter applies a DC voltage, typically 500 to 2,500 volts, to a motor's windings and gives a readout of the resistance of the insulation. Since the test is highly sensitive to moisture and temperature, technicians should perform all testing when the motor is at ambient temperature and humidity levels are relatively low.

Polarized insulation testing also reports on the condition of motor's insulation, but it takes into account that insulation molecules polarize as they are tested, changing the test results. Where insulation resistance testing is rather short in duration, polarized insulation testing is performed over a 10-minute interval, with readings taken at 1 and 10 minutes.

The value taken during the reading at the 10-minute interval then is divided by the reading taken at the 1-minute interval to determine the polarization index. Insulation that is in good condition will yield indexes above one and will not change from one test year to the next. Falling values indicates that insulation is in the process of failing.

Finally, technicians can use DC high-potential testing to detect weaknesses in the insulation that generally are missed by both insulation resistance and polarized insulation testing. The test provides information on the dielectric strength of the insulation and can identify areas within a motor's insulation that are likely to fault to ground.

A FLOWCHART APPROACH TO MOTOR REPAIR/REPLACE DECISIONS

Thomas H. Bishop, P.E., EASA Technical Support Specialist

Many decisions need to be made between the time a motor fails and when the final repair or replace option is chosen.

Using a flowchart like the one shown here helps us avoid overlooking any of the key steps in the decision process. Let's go through the flowchart and consider each decision point.

The first step in considering a failed motor is to assess whether it is actually suited for the application. This is a good question to ask regardless of whether the motor is to be repaired or replaced.

REPAIR CHOICES

If the motor suits the application, then the remaining decisions relate to repair choices. The first task is to determine the stator core's condition. If the condition is satisfactory, the decision process moves to assess other repair decisions. But if there is core damage, the cost to repair the damage must be weighed against the replacement cost. Keep in mind that a motor with special features may be significantly more expensive to replace and time-consuming to procure.

Following the core condition assessment, there are a series of questions that should be considered all together. These are:

- Has catastrophic failure occurred?
- Is there evidence of a prior catastrophic failure?
- Is the rotor damaged?
- Is there severe damage to other mechanical parts?
- Is it an EPAct or premium efficient motor?

If a catastrophic failure has occurred, or if there is evidence of a prior catastrophic failure, the repair cost should be weighed against the cost of a replacement. Now is a good time to consider the motor's suitability for the application. The failure may suggest application issues that were not recognized earlier, such as excessive radial load on the shaft and bearings. Catastrophic failures usually involve extreme damage to the stator core and windings, rotor, shaft, bearings, and end bracket. This damage may be so severe that the root cause is not apparent.

Even so, possible causes that led to the failure should be identified to prevent a recurrence.

Rotor damage can vary from surface smearing caused by contact with the stator, to bars and end rings melted on a die cast design, or bars lifted out of the slots and endrings broken on a fabricated design.

A flowchart approach can help with the motor repair/replace decision.

While smearing might be repaired economically, melted bars or bars lifted from their slots will, at a minimum, require rebarring.

The downside is that unless the motor is very large or special, rebarring is seldom an economic alternative.

If major core iron damage has occurred, new laminations add to the repair cost. In such a case, the damage can be considered catastrophic, shifting the economics of repair versus replacement more heavily toward replacement.

Other mechanical parts, such as the shaft or frame, can be damaged so badly they must be replaced. Here again, the economics of buying or making a new shaft, or buying a new frame, may make repairing the motor an unattractive choice.

THE EPACT/PREMIUM EFFICIENCY FACTOR

Each of these motor repair decision points has been well known for more than half a century. In the last decade, a new factor has been added: the energy-efficient motor.

These consist of the energy efficient motors included in the Energy Policy Act of 1992 (EPAct), and premium efficient motors.

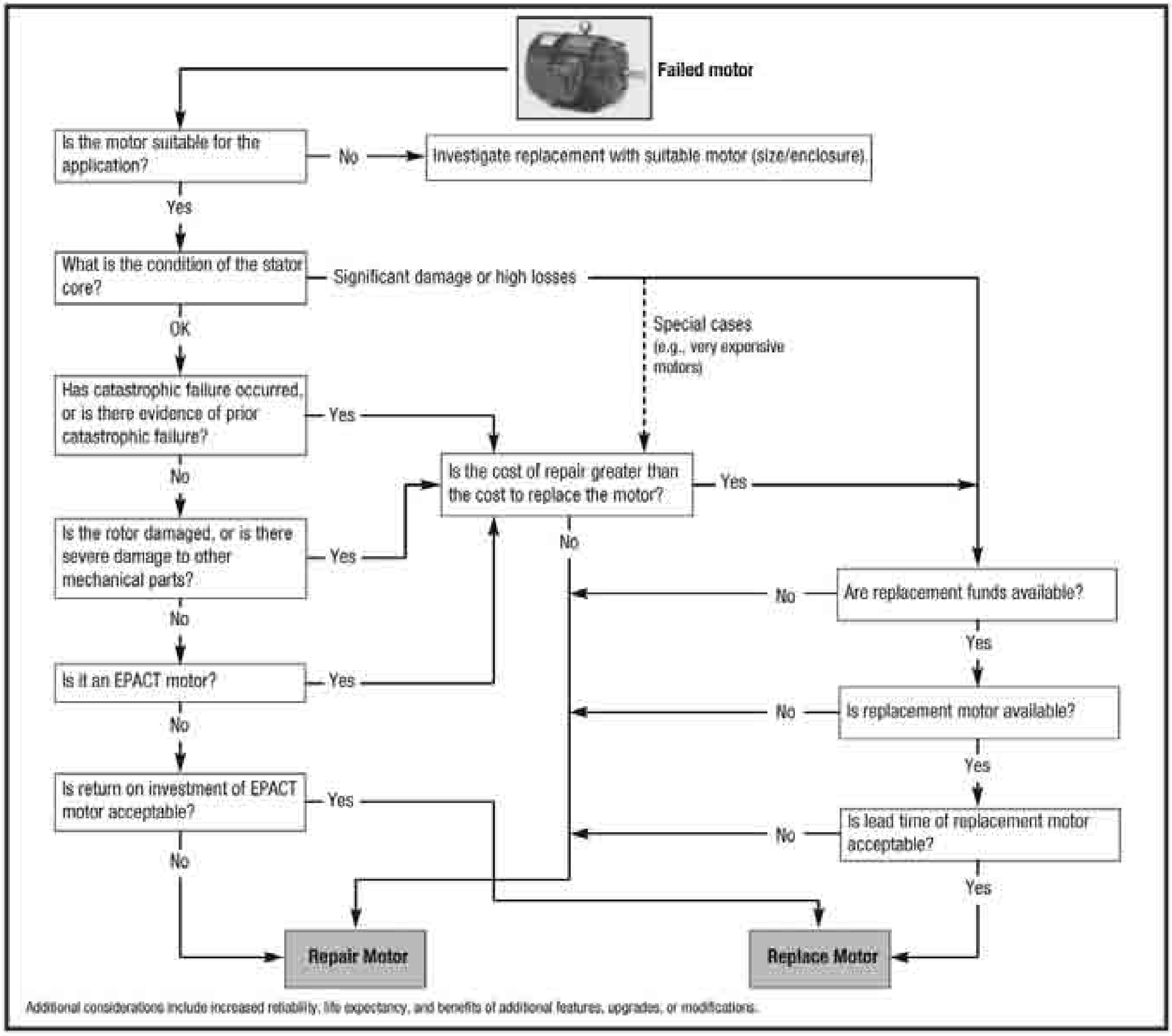
Regardless of the motor's label, the intent of a motor repair is to maintain the motor's original efficiency.

Energy-efficient motors have a greater volume of material than most earlier motor products. In particular, an energy-efficient motor may have a longer rotor and stator core, and more conductive material than a similarly sized motor that does not meet the definition of EPAct or of a premium motor as defined by National Electrical Manufacturers Association (NEMA).

Energy efficiency also introduces return on investment considerations to the repair-versus-replacement equation. This means considering the economic impact of all costs, including energy, and then determining which option provides the best overall benefits.

Thus, a new motor that is more energy efficient may be selected because of cost projections, based on the expected useful life of the motor or process.

Another key element in decision making is to determine whether funds are available for a replacement motor. This step often comes down to deciding which group within the company or plant is going to pay for the new motor. If the responsible


Failed motor
Is the motor suitable for the application?
No
Investigate replacement with suitable motor (size/enclosure).
Yes
What is the condition of the stator core?
Significant damage or high losses
Special cases (e.g., very expensive motors)
OK
Has catastrophic failure occurred, or is there evidence of prior catastrophic failure?
Yes
No
Is the cost of repair greater than the cost to replace the motor?
Yes
No
Is the rotor damaged, or is there severe damage to other mechanical parts?
Yes
No
Are replacement funds available?
No
Yes
Is it an EPACT motor?
Yes
No
Is replacement motor available?
No
Yes
Is return on investment of EPACT motor acceptable?
Yes
No
Is lead time of replacement motor acceptable?
No
Yes
Repair Motor
Replace Motor

Additional considerations include increased reliability, life expectancy, and benefits of additional features, upgrades, or modifications.

Failed motor repair/replacement decisions flowchart.

group lacks funds for a replacement, it may opt for a motor repair, so long as the cost is less than that of a new motor.

But let's assume that money is available for a new motor. The next decision point is availability. Standard feature motors, such as those that fall under EPAct rules, are normally stock items. However, larger motors or motors with special features may not be widely available from local suppliers and may have long delivery times.

FIVE LEVELS OF MOTOR REPAIR

Five levels of repair can be identified for squirrel cage induction motors. The first four represent an expanding scope of repairs. The fifth applies to motors that normally would be replaced, but present other factors to consider.

A Level 1 repair is a basic overhaul or reconditioning. It includes cleaning components, replacing bearings, and replenishing lubricants. It also includes inspection and testing during the incoming stage, the repair process, and during final testing.

Level 2 repairs include everything in Level 1, but add stator winding, varnish-resin treatment, worn bearing fit repair, and shaft straightening.

Level 3 adds stator rewinding; that is, replacing the windings and insulation system. Smaller motors with two or four poles are relatively simple to rewind. Special windings such as two-speed, or very lowspeed windings, can add considerable time and material to a repair.

Level 4 is the most comprehensive repair level; it encompasses all of the previous levels, and adds major lamination repair and/or rotor rebar. It also may include restacking or replacing the stator laminations, and shaft replacement. Before taking on major repairs at this level, you may first want to consider the motor replacement option. Not only will the cost of repair be high at Level 4, but the uncertainty associated with the size of the repair compounds the risk of successfully completing the job.

Level 5 repairs apply to motors that normally would be replaced except for special circumstances, such as the unavailability of a spare or replacement unit.

Level 5 could easily apply to any of the circumstances at the other four levels of repair. This level also includes misapplied motors and vintage pre U-frame motors. This latter group generally is not rated at voltages consistent with modern power systems, and has only Class A original windings.

Remember that motor repair costs generally go up as the scope of work increases.

Also keep in mind that no simple ratio exists between the factors of repairs and costs. By recognizing that there are five levels of repairs, decision makers will understand that considering only the cost of a motor repair versus replacement can be too simplistic to yield an accurate assessment.

10 QUESTIONS TO ANSWER BEFORE YOU CALL THE MOTOR SERVICE CENTER

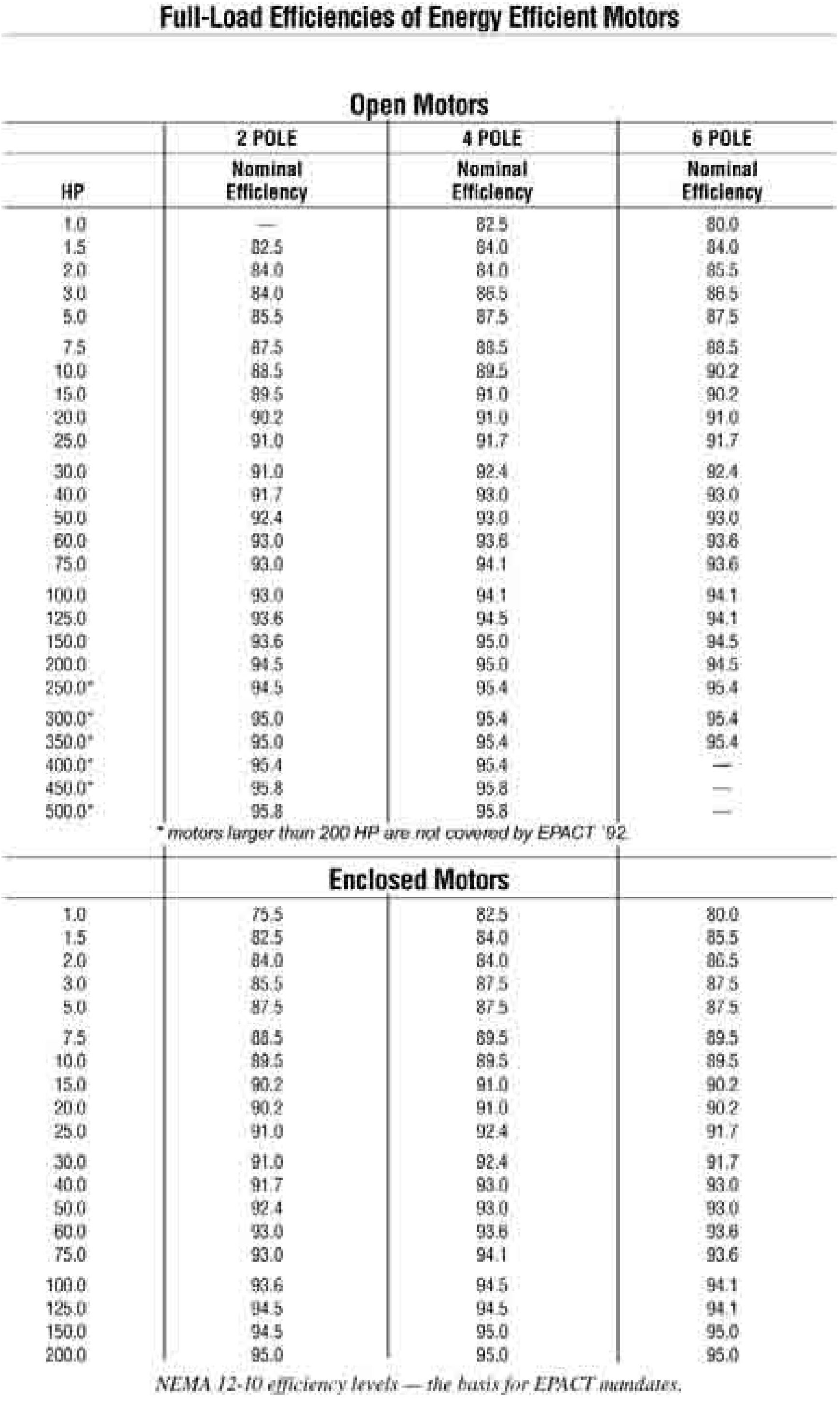
1. What is the basic nameplate information? (Include manufacturer, horsepower, speed, voltage, phase, enclosure, catalog, part and/or model number, frame size, and serial number.)
2. What does the motor operate? (A fan, blower, conveyor belt, pump?)
3. How does the motor drive the load? (Does it have a direct drive, or is it belted?)
4. Is there auxiliary equipment attached? (A clutch, gearbox, or brake?)
5. Why do you think the motor needs repair? (Does it smoke, not run, or need preventive maintenance?)
6. What is the motor's past repair history? (Is it a "problem motor"?)
7. How is the motor started? (Across the line, soft start, adjustable speed drive, part winding start, wye start, or delta run?)
8. What is the operating environment? (Indoors, outdoors, subject to hazardous fumes or dusts, or water spray?)
9. When do you need the motor back? Will you authorize overtime work if necessary?
10. Is the motor still under manufacturer's warranty?

EPACT AND ENERGY EFFICIENT ELECTRIC MOTORS

Jeffrey Hubert, Leeson Electric Corp.; the U.S. Department of Energy

It has probably been a topic of discussion since the beginnings of the electric motor industry. Certainly, it has been a major topic since the Arab oil embargo of the 1970s and, it seems, THE topic of discussion in the motor industry since the federal government's passage of the Energy Policy Act (EPACT). Motor efficiency: How completely an electric motor converts electricity into mechanical work. Does 80% of the electrical energy we feed into a motor become work "at the end of the shaft"? Does 90%? Yesterday, it was mostly a question for the curious. Today, driven first by higher energy costs, then by incentive programs of electric utilities, and most recently by federal legislation in the form of EPACT, which took effect in late 1997, motor efficiency has become an imperative.

Here, in a nutshell, is what U.S. law means to the industrial motor user, whether the motors are for replacement use on existing applications, or components of another machine. Three-phase, general-purpose, NEMA T frame motors of 1 through 200 HP, manufactured after October 24, 1997, must meet government-mandated efficiency levels. These EPACT levels are higher than those of most manufacturers' previous standard efficiency motors, but generally not higher than many manufacturers' longstanding "premium-efficiency" lines. So, in that sense, motors of the "new" efficiencies are not really all that new at all. The real difference is in how much more widespread their manufacture, availability and required became as of late 1997.



Full-Load Efficiencies of Energy Efficient Motors

Open Motors

HP	2 POLE Nominal Efficiency	4 POLE Nominal Efficiency	6 POLE Nominal Efficiency
1.0	—	82.5	80.0
1.5	82.5	84.0	84.0
2.0	84.0	84.0	85.5
3.0	84.0	86.5	86.5
5.0	85.5	87.5	87.5
7.5	87.5	88.5	88.5
10.0	88.5	89.5	90.2
15.0	89.5	91.0	90.2
20.0	90.2	91.0	91.0
25.0	91.0	91.7	91.7
30.0	91.0	92.4	92.4
40.0	91.7	93.0	93.0
50.0	92.4	93.0	93.0
60.0	93.0	93.6	93.6
75.0	93.0	94.1	93.6
100.0	93.0	94.1	94.1
125.0	93.6	94.5	94.1
150.0	93.6	95.0	94.5
200.0	94.5	95.0	94.5
250.0*	94.5	95.4	95.4
300.0*	95.0	95.4	95.4
350.0*	95.0	95.4	95.4
400.0*	95.4	95.4	—
450.0*	95.8	95.8	—
500.0*	95.8	95.8	—

** motors larger than 200 HP are not covered by EPACT '92.*

Enclosed Motors

HP	2 POLE Nominal Efficiency	4 POLE Nominal Efficiency	6 POLE Nominal Efficiency
1.0	75.5	82.5	80.0
1.5	82.5	84.0	85.5
2.0	84.0	84.0	86.5
3.0	85.5	87.5	87.5
5.0	87.5	87.5	87.5
7.5	88.5	89.5	89.5
10.0	89.5	89.5	89.5
15.0	90.2	91.0	90.2
20.0	90.2	91.0	90.2
25.0	91.0	92.4	91.7
30.0	91.0	92.4	91.7
40.0	91.7	93.0	93.0
50.0	92.4	93.0	93.0
60.0	93.0	93.6	93.6
75.0	93.0	94.1	93.6
100.0	93.6	94.5	94.1
125.0	94.5	94.5	94.1
150.0	94.5	95.0	95.0
200.0	95.0	95.0	95.0

NEMA 12-10 efficiency levels — the basis for EPACT mandates.

WHY IS MOTOR EFFICIENCY IMPORTANT?

Electric motors have a huge impact on overall energy usage. Between 30 and 40 percent of all fossil fuels burned in the world are used to generate electricity, and a large portion of that electricity goes to run motors. Nearly all estimates say that at least 60% of electricity in the United States is used to power motors.

Given the overwhelming number of small motors in consumer use, well over half of "motor power demand" falls to this (for now) unregulated motor segment. But that still leaves a sizable power demand within the industrial motor population, at current electric rates perhaps $30 billion worth of electrical power per year. This means that within the overall industrial motor segment, every percentage point gain in overall motor efficiency translates into $300 million of yearly savings. Maximizing industrial electric motor efficiency is clearly important. This is true in public energy policy terms, and environmentally in reduction of "greenhouse gases" associated with fossil fuel burning. Plus, it is also good business practice.

Under EPACT, many kinds of industrial motors are required to have efficiency levels nearly as high as the premium-efficiency motors.

WHAT EPACT SPECIFICALLY SAYS ABOUT MOTORS

Three-phase, 1 through 200 HP, general-purpose, T frame... those are the key elements to remember about which motors will or will not be covered by the EPACT guidelines in late 1997. Here are the specifics:

Any non-exempt motor manufactured after October 24, 1997, must meet the EPACT efficiency levels, as administered by the Department of Energy and related agencies. These levels are the same as those listed in the MG-1-1993 standards published by NEMA, the National Electrical Manufacturers Association. They are shown in Table 12-10 of that publication, so you will often hear the EPACT efficiency levels equated with "NEMA 12-10."

Note the emphasis in the previous paragraph on "manufactured". The law clearly does not require any motor user to replace an existing motor with a higher-efficiency model (though in some applications you might want to do so for economic reasons based on energy dollars saved.)

Two types of industrial motors: the ribbed frame version in the foreground is a good example of a NEMA T frame motor covered under EPACT through 200 HP. The larger motor is "above" NEMA frame size; therefore, it is exempt from EPACT mandates as now written.

And because motor companies are manufacturing motors and filling inventory channels all the time, there will certainly be standard motors "in the pipeline" for months and probably even years to come.

Customers may buy and install these pre-EPACT manufactured motors (presumably at a lower price than the newer high-efficiency models) as long as they're available. Similarly, the law makes no reference to used or rewound motors. Those may be bought at will, regardless of efficiency, though, over time, it's likely that the marketplace will demand a proven, if not certified, level of efficiency from rewound or otherwise reworked motors as well.

Note also the term "non-exempt" motor. While its scope is certainly widespread, covering perhaps half of all industrial motors, EPACT does not address all types of motors. Its focus is on small to medium-horsepower AC motors used in general industrial applications. For example, it states only three-phase 230/460 VAC motors from 1 through 200 HP. Further, these must be general-purpose, T frame motors with three-digit frame numbers, NEMA Design A or B, rated for continuous duty. Open and enclosed motors are included, as are two-pole, four-pole and six-pole designs (3600, 1800 and 1200 RPM). Imported motors, as well as those manufactured in the United States, are covered. These can be sold for replacement applications or incorporated into other machinery. Motors requiring third-party approvals such as explosion-proof designs come under the law's scope in October 1999. The law specifically applies to horizontal foot-mounted motors, and that includes foot-mounted motors that also have a NEMA C face mounting.

WHAT KINDS OF MOTORS ARE NOT INCLUDED IN EPACT?

"Definite-purpose" or "special-purpose" motors are exempt. The law defines definite-purpose motors as, among other things, those "which cannot be used in most general purpose applications". The law defines special-purpose motors as "other than general-purpose or definite-purpose motors, which have special operating characteristics or special mechanical consideration, or both, designed for a particular application". High-slip (NEMA Design D) or high-torque (NEMA Design C) motors are examples of special-purpose motors under this definition. Other examples are multi-speed or low-RPM motors and those designed for special voltages.

In addition, single-phase motors are exempt, as are any motors built in double-digit frames (42, 48 and 56, which are defined as fractional-horsepower frames), or for that matter in sub-fractional horsepower frame sizes. Of course, it's not uncommon to find motors of up to 3 HP built in NEMA 56 frames. Even though they are clearly 1 HP or greater, these are exempt.

In reality, the whole issue of how much or how little single-phase or fractional horsepower motors are affected revolves around setting standards for what the law generically refers to as "small motors," meaning under 1 HP, any motors in two-digit NEMA frame sizes, or sub-fractional motors. The law does not differentiate between single-phase and three-phase "small motors", but the greatest population of fractional and sub-fractional motors are, in fact, single phase. (There are plenty of single-phase motors also built in 140, 180 and 210 frame sizes, and the federal government may eventually address those as well.)

Exempt From EPACT

- Motors with no base or provisions for a base (example: NEMA C face, less base)
- Motors having customer-defined base or feet
- A motor having a customer-defined shaft, if the motor cannot be used as general purpose
- Two-digit frames (example: NEMA 56 or 56HZ)
- TENV and air over – TEAO and open air over designs
- Inverter duty motors (but "inverter rated" general purpose motors covered)
- Multi-speed motors
- Frame size larger than NEMA assignment (NEMA 182T to 213T, not 182T to 184T). Frame size smaller motors are covered, i.e., 184T instead of 213T.
- 50 Hertz motors (but 50/60 Hertz are covered)
- 200, 575 volt or other special voltage motors (that cannot be used at 230 or 460 volts)
- Motors having NEMA Design C or D torques

The Department of Energy has adopted standards for most "small motors". There are other issues peculiar to single-phase motors that must also be resolved. These include what types of single-phase motors are covered, how the term "general purpose" applies, what efficiencies will be mandated, and what test method will be used.

Because there are many types of single-phase motors, would there have to be differing standards for each type? IEEE 114, the standard that prescribes single-phase motor test procedures, was inactivated in 1992. More fundamentally, would inherently inefficient designs, such as the inexpensive shaded pole motors often used in consumer appliances, be exempt from regulation — or at the other extreme possibly even prohibited, either by direct legislation or as part of requirements for overall appliance efficiency? (In many cases, however, small motors on appliances may well already be affected within the scope of overall appliance efficiency requirements.)

WHAT MAKES ONE MOTOR MORE EFFICIENT THAN ANOTHER?

Before we answer this question, let's be sure we're comfortable with one key fact:

Industrial-duty electric motors are, across the board, an extremely efficient means of converting energy into useful work. This is especially true for three-phase motors, plus the majority of single-phase designs used in industrial applications. These motor designs include permanent split capacitor, capacitor start, and capacitor start/capacitor run. After all, in a 94% efficient motor, only 6% of the electrical energy is not converted to useable mechanical power. Internal combustion engines are less than half as efficient as even most standard-efficiency electric motors.

Electric motor users, designers and manufacturers have nothing to be ashamed of.

It's just that — for a cost in active material, primarily copper and steel — there are ways to make what's good even better. That's what EPACT is all about.

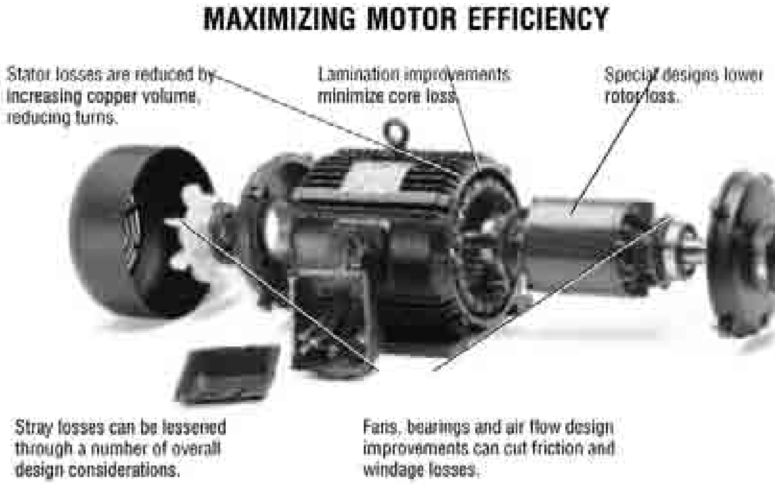
So back to the question of what makes a motor efficient or, for that matter, inefficient. We've already provided a working man's definition of efficiency: The ability of a motor to convert electrical energy into mechanical work. But why is one motor — sometimes as if by magic — more efficient than another?

Well, first of all, it's not magic. In fact, the processes for increasing motor efficiency are well-known and not at all mystical. Without getting too deeply into the disciplines of electrical or mechanical engineering, here are the basics:

Maximizing motor efficiency involves minimizing energy lost during the motor's operation. For AC polyphase motors, this lost energy comes in several different forms, all clearly delineated in, among other places, NEMA standards:

- Core loss, the energy needed to magnetize the steel lamination stack of a motor.
- Friction and windage loss, the result of bearing friction and air resistance caused by motor cooling fans and the rotor itself.
- Stator winding resistance, which creates heat as current attempts to flow through stator windings.
- Rotor resistance, again showing up as heat, this time from electrical resistance in rotor bars and end rings.
- Stray load loss, the sum of the remaining small electrical and magnetic losses that cannot be measured directly.

Core loss and friction and windage loss are considered "no-load losses" because they exist in essentially the same amounts regardless of the motor load, including no load at all. Taken together, these "no-load losses" account for one third or less of total motor losses when a motor is operating under typical loading. Stator, rotor and stray load losses change as the motor is loaded and will increase with load. Combined, these losses account for two-thirds or more of the total loss in a typical design.


MAXIMIZING MOTOR EFFICIENCY

Stator losses are reduced by increasing copper volume, reducing turns.

Lamination improvements minimize core loss.

Special designs lower rotor loss.

Stray losses can be lessened through a number of overall design considerations.

Fans, bearings and air flow design improvements can cut friction and windage losses.

Just as the definitions of losses are straightforward, so are the means to control them.

- Core loss is minimized through higher grades of lamination steel, thinner laminations, and a longer lamination stack.
- Friction and windage losses are decreased by improved bearings, plus smaller fans and better air flow design.
- Stator losses are lessened by using more wire or heavier gauge wire, or by reducing end turns.
- Rotor losses can be reduced through special designs and larger conductive bars.
- Stray losses are typically reduced by a combination of design factors, including an optimized air gap between the rotor and stator, and the number and shape of lamination slots.

Given the fact that the majority of motor losses are attacked by adding costly material, it's not hard to see why today's premium-efficiency motors cost about 20-25% more than comparable standard efficiency designs. As one engineer has put it, "To make a higher efficiency motor, you don't sprinkle it with pixie dust, you sprinkle it with dollar bills."

HOW IS MOTOR EFFICIENCY MEASURED?

The three-phase motor standard, IEEE 112, is very much in regular use. That's why IEEE 112, or the essentially identical CSA Standard C390, have been adopted as the authoritative procedures for determining motor efficiency under EPACT. Both standards, because they take into account all losses, are by most accounts more stringent than the other standards common throughout the world, including IEC 34.2, the essentially identical British standard BS 269, or the Japanese standard JEC 37, which ignores stray load losses altogether.

Dynamometer testing is required to determine accurate motor efficiencies.

With either the IEEE or CSA standards, for motors from 1 through 200 HP, the approved method of testing under EPACT (called Method B) involves using a dynamometer, a device that can place a motor under measurable and repeatable load.

Under EPACT, as currently written, motor manufacturers must have a testing/certification program in place to demonstrate compliance. Some manufacturers, including LEESON, already have undergone third-party certification of their test labs.

The result of this testing, as far as meeting EPACT requirements, will be to gather data to establish a "nominal full-load efficiency". Nominal efficiency can be thought of as the average efficiency measured over a defined sample of the same motor model. The exact nominal efficiency will not actually be stamped on the nameplate, however. That value will be selected from a table of standard nominal efficiency values. For example, if a sample of 10 HP open motors has an average efficiency of at least 87.6%, it will be stamped with a "NEMA Nominal Efficiency" of 87.5%. These efficiency bands are intended to eliminate minor, essentially irrelevant efficiency differences that may well be the result of ordinary testing variances. Motors having efficiencies within the bands can be treated as operationally equivalent. In addition to nameplating requirements, EPACT also calls for disclosure of efficiency information in marketing materials.

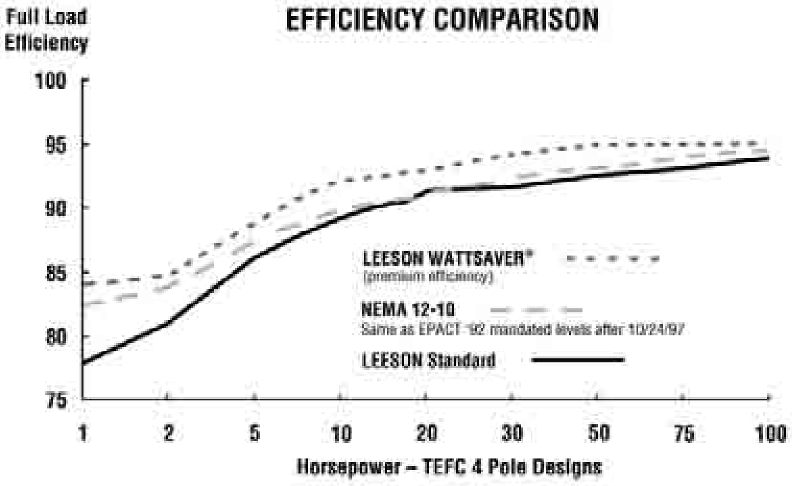
THE ECONOMICS OF MOTOR EFFICIENCY

There had been concern that EPACT, by mandating general-purpose motor efficiencies, would limit the motor buyer's options and take economics out of the buying equation. In fact, by increasing the range of efficiency choices, EPACT has expanded the possibilities. Buyers can choose from EPACTefficiency motors, or perhaps premium-efficiency NEMA Design B motors exceeding EPACT mandates. On the other hand, higher-torque NEMA Design C motors, which are exempt from EPACT mandates, may provide a lower-cost alternative for applications requiring four-pole or six-pole speeds. And some standard-efficiency motors manufactured before the EPACT deadline continue to be available for sale from suppliers' stocks. You can use the Annual Energy Cost Worksheet to help calculate how much given motors will cost to operate for a year, then draw your own comparisons as to the payback you want.

The key factors in any energy-saving equation may be the number of hours the motor is run and at what load. If it runs a lot at nearly full load, chances are the balance will tip toward higher efficiency. At the extreme, the savings may be so great as to warrant taking a perfectly serviceable older motor off line and upgrading to a new, higher-efficiency one.

If the usage is less continuous or at lower loads, it's unlikely that upgrading a working motor will make sense.

Other application considerations also come into play. For example, on some direct drive centrifugal applications, such as a fan or pump, the somewhat higher operating RPM common on higher-efficiency motors (the result of less "slip") can drive up the load and output enough to offset the energy savings. On centrifugal loads, the horsepower needed increases by the cube of the speed, so a small increase in

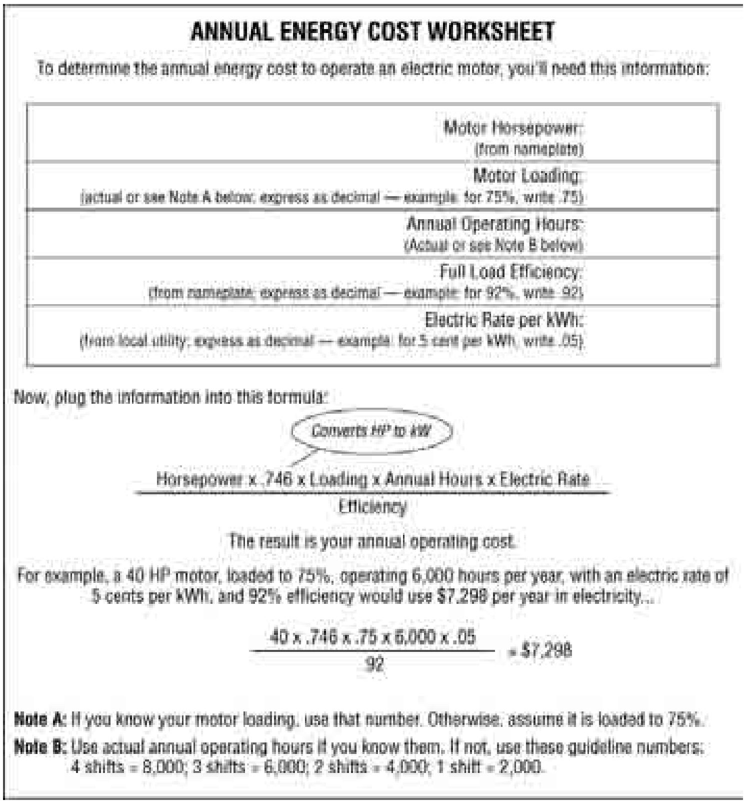


Example of how one manufacturer's standard and premium efficiency motors compare today with EPACT mandates. In most cases, EPACT, or NEMA 12-10 levels, are higher than standard, but lower than today's current premium efficiency motors.

speed will have a correspondingly greater impact on load. Of course, higher RPM could also increase overall operating efficiency by allowing a piece of machinery to finish its job more quickly. So, as always, the results will vary with the application. Some designs that concentrate only on efficiency can exhibit some unusual characteristics. One example is high locked rotor amps, which could affect wiring and starters, especially in the "next generation" of motor efficiency.

To understand the issues behind these "next generation" motors, you must first understand that EPACT-efficiency motors are essentially efficiency optimizations of standard NEMA Design B motors. They must meet standard Design B performance in areas other than efficiency. These include such key requirements as locked rotor amp draw, torque and so forth. These requirements limit how much design factors can be employed to improve efficiency.

Therefore, to avoid going to "exotic" means to boost efficiency still further, some of these requirements must be relaxed. To address this future trend, NEMA created a new motor type, Design E. (See Design E efficiency table) Design E standards allow a great deal higher locked rotor amps (as much as 50% or more above Design B) as a tradeoff for notching efficiency up a step further by reducing rotor resistance. With lower rotor resistance also comes lower starting torque, which may make Design E machines unsuitable for some hard-to-start loads. Plus, the motor speed will be stepped up a bit further, due to less slip, again having an impact particularly on centrifugal loads.



ANNUAL ENERGY COST WORKSHEET

To determine the annual energy cost to operate an electric motor, you'll need this information:

Motor Horsepower:
(from nameplate)

Motor Loading:
(actual or see Note A below; express as decimal — example: for 75%, write .75)

Annual Operating Hours:
(Actual or see Note B below)

Full Load Efficiency:
(from nameplate; express as decimal — example: for 92%, write .92)

Electric Rate per kWh:
(from local utility; express as decimal — example: for 5 cent per kWh, write .05)

Now, plug the information into this formula:

Converts HP to kW

$$\frac{\text{Horsepower} \times .746 \times \text{Loading} \times \text{Annual Hours} \times \text{Electric Rate}}{\text{Efficiency}}$$

The result is your annual operating cost.

For example, a 40 HP motor, loaded to 75%, operating 6,000 hours per year, with an electric rate of 5 cents per kWh, and 92% efficiency would use $7,298 per year in electricity...

$$\frac{40 \times .746 \times .75 \times 6{,}000 \times .05}{92} = \$7{,}298$$

Note A: If you know your motor loading, use that number. Otherwise, assume it is loaded to 75%.

Note B: Use actual annual operating hours if you know them. If not, use these guideline numbers:
4 shifts = 8,000; 3 shifts = 6,000; 2 shifts = 4,000; 1 shift = 2,000.

Another possible disadvantage to higher-efficiency motors, of whatever design, could be a greater cost to repair, because they require more carefully controlled service procedures, plus more and costlier rewind materials. And, in those cases where mounting space is tight, high-efficiency motors, because most have a longer stack, could be a tight squeeze.

Now, a word on the durability of high-efficiency motors. In general, it should be enhanced compared with standard efficiency designs because of improved materials, less heat generated and a somewhat larger core size, which will tend to fend off the extra heat stress of peak loads or start/stop operation. Still, this durability difference could be difficult to measure given the reliability and long life of virtually all industrial-duty AC polyphase motors. The best statement might be this: Rest assured that high efficiency motors, like their standard efficiency counterparts, will be among the most reliable pieces of industrial machinery you'll ever own.

NOW THAT EPACT IS HERE, WHAT OTHER CHANGES MIGHT WE EXPECT?

Of more immediate interest is the future of utility rebates. Certainly, the proliferation of such utility programs has focused attention on the value of stepping up motor efficiency. Rebates may also have helped utilities avoid the hassles and cost of some new power plant construction — though overall efficiency gains by industry probably played a greater role than motors themselves.

But now, given the fact that the majority of new industrial motors will now be high-efficiency by requirement, of what value are the rebates? Put another way: With the force of law behind the motor efficiency movement, what further incentive could be necessary?

The answer, it seems, is that while rebates will not apply to mandated-efficiency motors, they may apply to motors that "go the next step" to an even higher efficiency. It's likely that motor manufacturers will continue to build premium-efficiency lines of motors, over and above their mandated-efficiency lines — whether these are further optimizations of current designs, or the new Design E motors explained earlier. And it's likely that in some areas of the country where generating capacity is nearly fully utilized, rebates for the new premium-efficiency motors will continue to make sense. This comprises basically the "industrial heartland," plus the Northeast, Northwest and California.

Motor Efficiency and Rebate Levels

	Tier 1	Totally Enclosed Fan-Cooled and Explosion-Proof Motors Minimum Efficiencies			Open Drip-Proof Motors Minimum Efficiencies			Tier 2	Totally Enclosed Fan-Cooled and Explosion-Proof Motors Minimum Efficiencies			Open Drip-Proof Motors Minimum Efficiencies		
		RPM			RPM				RPM			RPM		
Motor HP	Rebate Per Motor	3600	1800	1200	3600	1800	1200	Rebate Per Motor	3600	1800	1200	3600	1800	1200
2	$40	84.0	84.0	86.5	84.0	84.0	85.5	$75	86.5	86.5	88.5	86.5	86.5	87.5
3	$40	85.5	87.5	87.5	84.0	86.5	86.5	$75	87.5	89.5	89.5	86.5	88.5	88.5
5	$50	87.5	87.5	87.5	85.5	87.5	87.5	$95	89.5	89.5	89.5	87.5	89.5	89.5
7.5	$80	88.5	89.5	89.5	87.5	88.5	88.5	$120	91.0	91.7	91.7	90.2	91.0	91.7
10	$90	89.5	89.5	89.5	88.5	89.5	90.2	$140	91.7	91.7	91.7	91.0	91.7	92.4
15	$120	90.2	91.0	90.2	89.5	91.0	90.2	$140	92.4	93.0	92.4	91.7	93.0	92.4

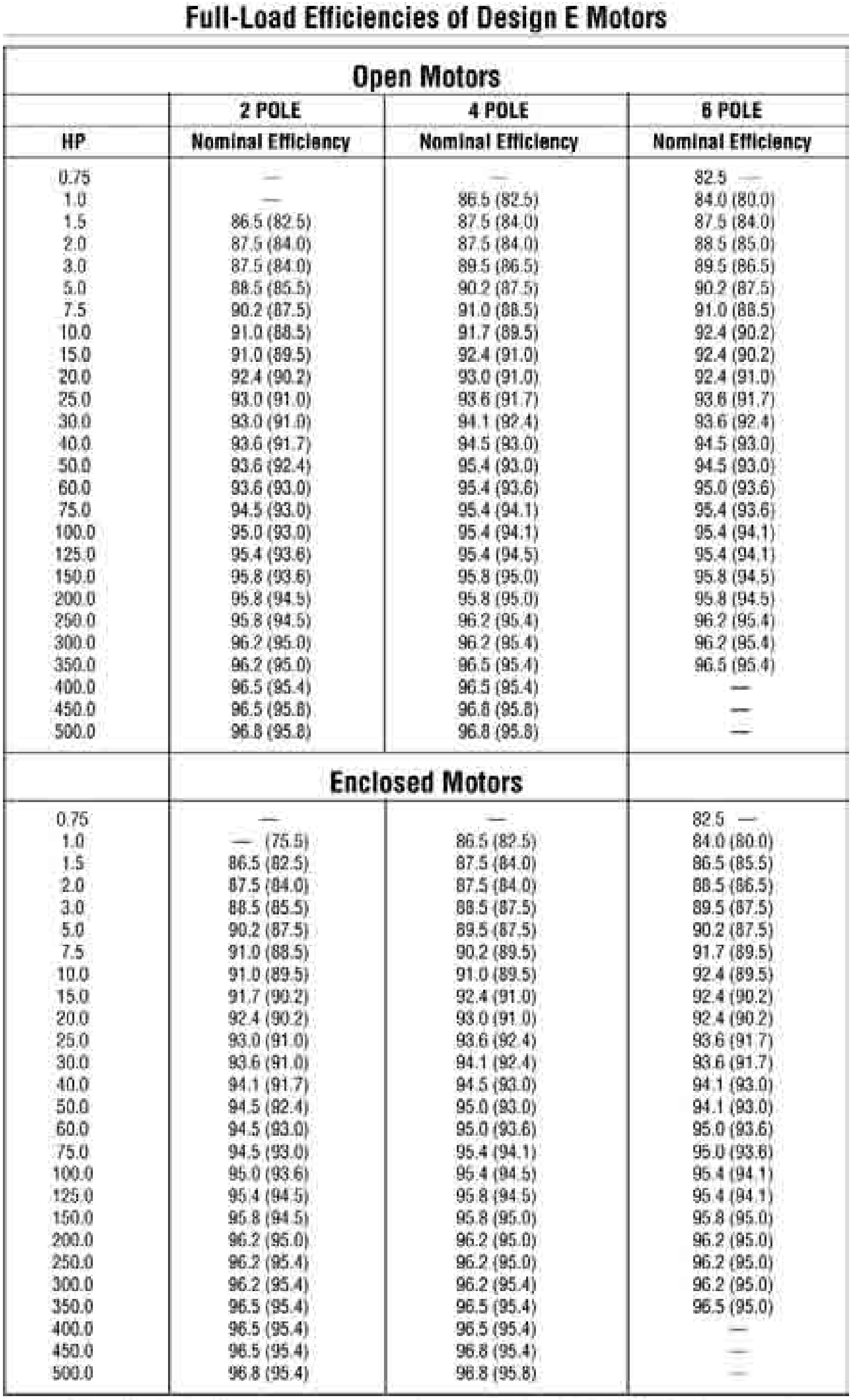
Example of two-tier utility rebate program.

Still, even where motor-only rebates might continue, the emphasis by utilities will be more and more on a systems approach to saving energy. Canada provides an example. In Canada, which began its provincial and federal efforts to boost motor efficiency years before the United States, utilities now offer no efficiency rebates at all, feeling that their objective to boost the population of energy-efficiency motors has been achieved over the past several years. The market share of high-efficiency motors in now reported to be well above 50% in most provinces, and more than 75% in British Columbia, which has been under EPACT-level efficiency mandates since the beginning of 1995.

The point is, Canadian utilities have demonstrated in a very practical fashion that rebates and focused motor-efficiency efforts are clearly the first step, to be followed by programs addressing inefficiencies throughout a motor-driven system. It's easy to see the value of such an approach. While motor efficiencies, taken alone, continue to push into the mid 90% area, overall system efficiencies may well be as low as 50% — the result of oversized, mismatched or inefficient machinery, or poor operating and maintenance procedures. Simply put, the remaining few percentage points of inefficiency that might be wrung from a motor, at considerable additional effort and cost, are dwarfed by the dozens of percentage points of gain possible through a comprehensive systems approach.

This is especially true when the system is relatively high horsepower and operates all or most of the time, such as many fans, blowers or pumps.

Very often, the systems approach in such cases is equated to the use of adjustable speed drives to modulate output, rather than simply using single-speed motors and throttling techniques such as valves or dampers. In reality, that is only one important tool in the solution that involves an overall effort to match system performance more closely to process requirements — an effort that the Department of Energy says could save 10 times more energy than motor optimization alone. Already, programs to encourage such "process optimization" through financial assistance have taken root under the auspices of utilities and other groups, not only in Canada, but also in the U.S. Midwest.



Full-Load Efficiencies of Design E Motors

	Open Motors		
	2 POLE	4 POLE	6 POLE
HP	Nominal Efficiency	Nominal Efficiency	Nominal Efficiency
0.75	—	—	82.5 —
1.0	—	86.5 (82.5)	84.0 (80.0)
1.5	86.5 (82.5)	87.5 (84.0)	87.5 (84.0)
2.0	87.5 (84.0)	87.5 (84.0)	88.5 (85.0)
3.0	87.5 (84.0)	89.5 (86.5)	89.5 (86.5)
5.0	88.5 (85.5)	90.2 (87.5)	90.2 (87.5)
7.5	90.2 (87.5)	91.0 (88.5)	91.0 (88.5)
10.0	91.0 (88.5)	91.7 (89.5)	92.4 (90.2)
15.0	91.0 (89.5)	92.4 (91.0)	92.4 (90.2)
20.0	92.4 (90.2)	93.0 (91.0)	92.4 (91.0)
25.0	93.0 (91.0)	93.6 (91.7)	93.6 (91.7)
30.0	93.0 (91.0)	94.1 (92.4)	93.6 (92.4)
40.0	93.6 (91.7)	94.5 (93.0)	94.5 (93.0)
50.0	93.6 (92.4)	95.4 (93.0)	94.5 (93.0)
60.0	93.6 (93.0)	95.4 (93.6)	95.0 (93.6)
75.0	94.5 (93.0)	95.4 (94.1)	95.4 (93.6)
100.0	95.0 (93.0)	95.4 (94.1)	95.4 (94.1)
125.0	95.4 (93.6)	95.4 (94.5)	95.4 (94.1)
150.0	95.8 (93.6)	95.8 (95.0)	95.8 (94.5)
200.0	95.8 (94.5)	95.8 (95.0)	95.8 (94.5)
250.0	95.8 (94.5)	96.2 (95.4)	96.2 (95.4)
300.0	96.2 (95.0)	96.2 (95.4)	96.2 (95.4)
350.0	96.2 (95.0)	96.5 (95.4)	96.5 (95.4)
400.0	96.5 (95.4)	96.5 (95.4)	—
450.0	96.5 (95.8)	96.8 (95.8)	—
500.0	96.8 (95.8)	96.8 (95.8)	—
	Enclosed Motors		
0.75	—	—	82.5 —
1.0	— (75.5)	86.5 (82.5)	84.0 (80.0)
1.5	86.5 (82.5)	87.5 (84.0)	86.5 (85.5)
2.0	87.5 (84.0)	87.5 (84.0)	88.5 (86.5)
3.0	88.5 (85.5)	88.5 (87.5)	89.5 (87.5)
5.0	90.2 (87.5)	89.5 (87.5)	90.2 (87.5)
7.5	91.0 (88.5)	90.2 (89.5)	91.7 (89.5)
10.0	91.0 (89.5)	91.0 (89.5)	92.4 (89.5)
15.0	91.7 (90.2)	92.4 (91.0)	92.4 (90.2)
20.0	92.4 (90.2)	93.0 (91.0)	92.4 (90.2)
25.0	93.0 (91.0)	93.6 (92.4)	93.6 (91.7)
30.0	93.6 (91.0)	94.1 (92.4)	93.6 (91.7)
40.0	94.1 (91.7)	94.5 (93.0)	94.1 (93.0)
50.0	94.5 (92.4)	95.0 (93.0)	94.1 (93.0)
60.0	94.5 (93.0)	95.0 (93.6)	95.0 (93.6)
75.0	94.5 (93.0)	95.4 (94.1)	95.0 (93.6)
100.0	95.0 (93.6)	95.4 (94.5)	95.4 (94.1)
125.0	95.4 (94.5)	95.8 (94.5)	95.4 (94.1)
150.0	95.8 (94.5)	95.8 (95.0)	95.8 (95.0)
200.0	96.2 (95.0)	96.2 (95.0)	96.2 (95.0)
250.0	96.2 (95.4)	96.2 (95.0)	96.2 (95.0)
300.0	96.2 (95.4)	96.2 (95.4)	96.2 (95.0)
350.0	96.5 (95.4)	96.5 (95.4)	96.5 (95.0)
400.0	96.5 (95.4)	96.5 (95.4)	—
450.0	96.5 (95.4)	96.8 (95.4)	—
500.0	96.8 (95.4)	96.8 (95.8)	—

Design E standards for the "next generation" of motor efficiency. NEMA 12-10 values are shown in parentheses. Through 200 HP, NEMA 12-10 efficiencies are the basis for the EPACT mandates, which are to take effect in October 1997.

Plus, the Department of Energy, through its Motor Challenge program, continues to showcase the advantages of managing all parts of a motor-driven system. And this overall systems approach, we believe, will quite appropriately represent the efficiency trend of the future.

INDUCTION MOTORS: PART I - ANALYSIS

S.E. Zocholl

INTRODUCTION

Is there ever enough information at hand to analyze a motor problem? Consider this example:

A plant process is shut down for maintenance once every two years. After a scheduled maintenance, an 1800 rpm, 2.4 kV, 1200 hp pump motor tripped on startup. The plant is under new management, and few files are available. However, records list the motor starting time as 20 seconds and the locked rotor time as 14 seconds. The motor bus is fed by a transformer with a 5.6 percent impedance that dips the terminal voltage 75 percent of nominal on starting. The plant manager wants a report and a recommendation to upgrade the protection.

Here is an overview of what needs to be done:

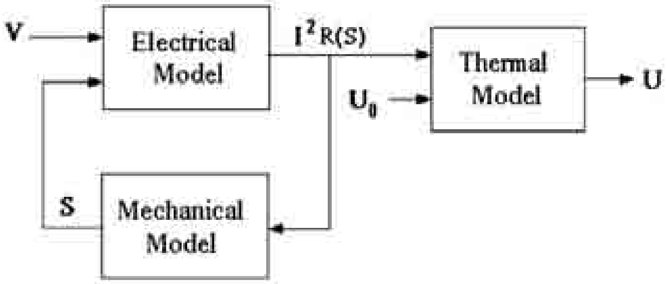


Figure 1: Motor Analysis Block Diagram

Induction motor starting can be analyzed using electrical, mechanical, and thermal models that interact as diagrammed in Figure 1. In the electrical model, the voltage, V, and the slip, S, determine the rotor current. The summation of all torques acting on the motor shaft comprises the mechanical model. Here, the driving torque developed by the motor is resisted by the load torque and the moment of inertia of all the rotating elements, all of which are slip dependent.

The thermal model is the equation for heat rise due to current in a conductor determined by the thermal capacity, the thermal resistance, and the slip dependent I2R watts. As the ultimate protection criteria, the thermal model is used to estimate the rotor temperature, U, resulting from the starting condition with initial temperature U0. A recursive solution using finite time increments is used because the rotor impedance changes continuously with slip.

As complex as this process may appear, we can add a few standard values and do the complete analysis with the meager information given. In fact, using the SEL-5802 Motor Modeling Program, it can be done in less than a minute. Here is how.

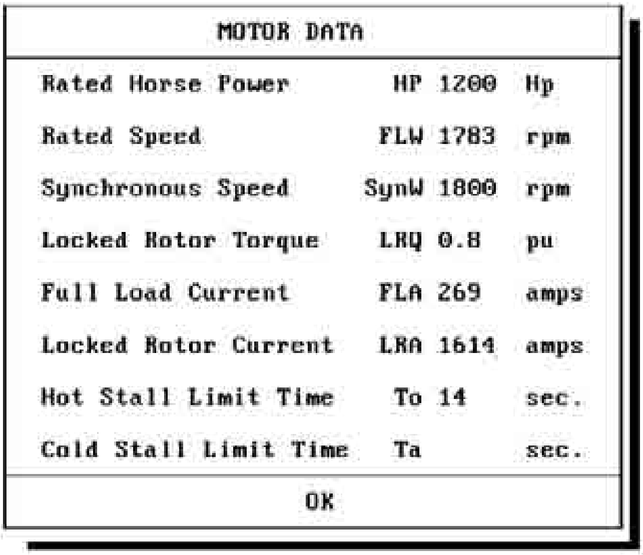
ESTIMATING INPUT DATA

Figure 2 is the menu of the data which defines the electrical and the thermal model of the motor.

To fill in the data, we have used the stated voltage and horse power to calculate the full load current:

$$FLA = \frac{746 \cdot HP}{0.8 \cdot \sqrt{3} \cdot V} = \frac{746 \cdot 1200}{0.8 \cdot \sqrt{3} \cdot 2.400} = 269 \qquad (1)$$

We used 6 times FLA as the locked rotor current and calculated the full load speed using one percent slip at full load. Depending on the class and application of the motor, the locked rotor torque can take on values of 0.8, 1.0, or 1.2. The value of 0.8 is the appropriate value for a pump motor.



```
                    MOTOR DATA
Rated Horse Power          HP 1200   Hp
Rated Speed               FLW 1783   rpm
Synchronous Speed        SynW 1800   rpm
Locked Rotor Torque       LRQ 0.8    pu
Full Load Current         FLA 269    amps
Locked Rotor Current      LRA 1614   amps
Hot Stall Limit Time       To 14     sec.
Cold Stall Limit Time      Ta        sec.
                        OK
```

Figure 2: Menu of Essential Motor Data

DEFINING THE ELECTRICAL MODEL

The program uses the motor data in the motor menu to generate the impedances of the motor including equations for the slip dependent positive- and negative-sequence rotor resistance and reactance:

Locked rotor current:

$$I_L = \frac{LRA}{FLA} = 6.0 \qquad (2)$$

Rotor resistance at rated speed

$$R_0 = \frac{SynW - FLW}{SynW} = 0.01 \qquad (3)$$

Locked rotor resistance

$$R_1 = \frac{LRQ}{I_L^2} = 0.022 \qquad (4)$$

Stator resistance

$$R_S = \frac{R_0}{5} = 0.002 \qquad (5)$$

Total series resistance

$$R = R_1 + R_S = 0.024 \qquad (6)$$

Total series impedance

$$Z = \frac{1}{I_L} = 0.167 \qquad (7)$$

Total series reactance

$$X = \sqrt{Z^2 - R^2} = 0.165 \qquad (8)$$

Locked rotor reactance

$$X_1 = \frac{X}{2} = 0.0082 \qquad (9)$$

Stator reactance

$$X_S = X - X_1 = 0.082 \qquad (10)$$

Rotor reactance at rated speed

$$X_0 = (\tan(12.75°))(1 + R_0 + R_S) = 0.147 \qquad (11)$$

Positive-sequence rotor resistance

$$R_{r+} = (R_1 - R_0) \cdot S + R_0 \qquad (12)$$

Positive-sequence rotor reactance

$$X_{r+} = (X_1 - X_0) \cdot S + X_0 \qquad (13)$$

Negative-sequence rotor resistance

$$R_{r-} = (R_1 - R_0) \cdot (2 - S) + R_0 \qquad (14)$$

Negative-sequence rotor reactance

$$X_{r-} = (X_1 - X_0) \cdot (2 - S) + X_0 \qquad (15)$$

The above calculations result in the equivalent circuit shown in Figure 3. We can now have the program calculate the characteristic of rotor torque and current versus slip at rated volts by varying the slip from 1 to 0. This characteristic, shown in Figure 4, will be useful in defining the input watts of the thermal and mechanical models.

DEFINING THE MECHANICAL MODEL

The mechanical model is the equation expressing the summation of torques acting on the shaft:

$$(Q_M - Q_L) = M\frac{d\omega}{dt} \qquad (16)$$

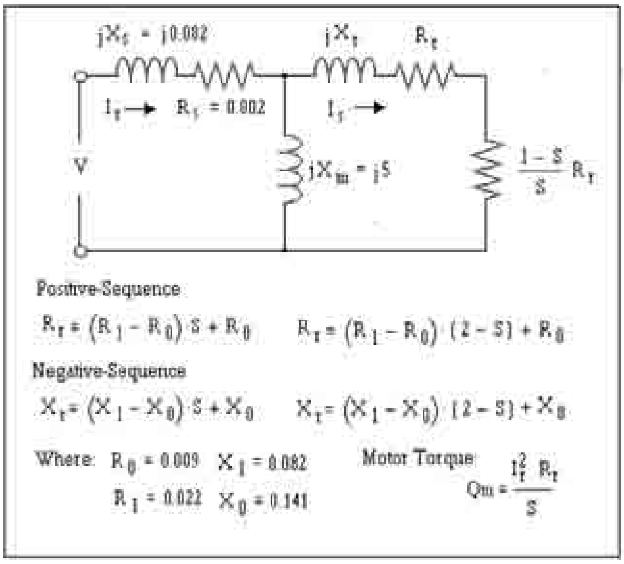


Figure 3: Motor Equivalent Circuit

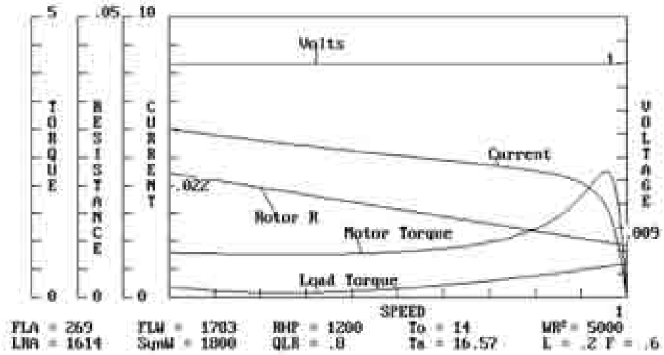


Figure 4: Current and Torque Versus Slip

where QM is the motor torque, QL is the load torque, M is the combined moment of inertia of the motor and the drive, and £s is the velocity. The equation expressed in time discrete form and solved for slip becomes:

$$(Q_M - Q_L) = M\frac{\omega - \omega_0}{DT} \qquad (17)$$

$$\omega = \frac{(Q_M - Q_L)}{M}DT + \omega_0 \qquad (18)$$

$$S = (1 - \omega)$$

The electromechanical power developed by the rotor is represented by the losses in the variable load resistor in Figure 3. Consequently, the positive-sequence mechanical power is:

$$P_M = I_{r+}^2 \cdot \frac{1-S}{S} R_{r+} \qquad (19)$$

where Ir+

2 is positive-sequence rotor current. Dividing the power PM by the velocity, the (1 - S) gives the motor torque:

$$Q_M = \frac{I_{r+}^2 \cdot R_{r+}}{S} \quad (20)$$

Figure 5 shows the typical contour of the load torque versus speed curve of a pump or fan. The load torque is characterized by an initial breakaway torque value, L, and momentary decrease followed by the increase to its final value, F. The program uses the empirical equation:

$$Q_L = L \cdot (1-\omega)^5 + F \cdot \omega^2 \quad (21)$$

Figure 4 shows the load torque relative to the motor torque. The torque difference (QM - QL) is the accelerating torque as expressed by equation (16). The accelerating power and the moment of inertia determine the time it takes the motor to reach the peak torque and attain rated speed.

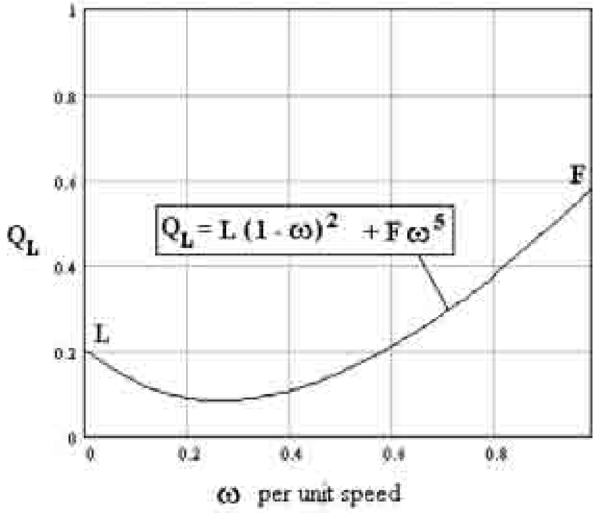


Figure 5: Contour of Load Torque

The mechanical data is entered into the menu shown in Figure 6. Typical values for the load are shown with the moment of the inertia specified in units of lb-ft2. Since all of the model parameters are specified in per unit of motor base values, the WR2 is converted to the inertia constant, M, using the following relation:

$$M = \frac{WR^2}{g} \cdot \frac{2\pi}{60} \cdot \frac{SynW}{Q_R} \quad (22)$$

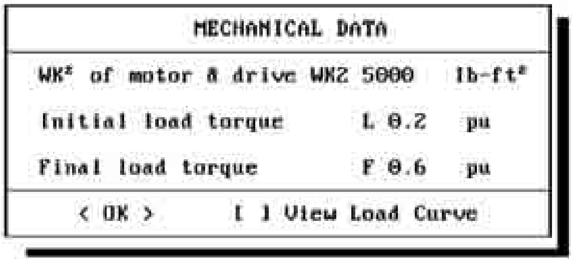
where g is the acceleration due to gravity, SynW is the synchronous speed, and QR is the torque calculated from rated speed and horse power:

$$Q_R = 5252 \cdot \frac{RHP}{FLW} \quad (23)$$

With this motor and load, the moment of inertia of 5000 lb-ft2 produces a 23-second starting time.

DEFINING THE THERMAL MODEL

The differential equation for the temperature rise in a conductor, neglecting heat loss is:



```
MECHANICAL DATA
WK² of motor & drive WK2 5000   lb-ft²
Initial load torque     L 0.2   pu
Final load torque       F 0.6   pu
< OK >      [ ] View Load Curve
```

Figure 6: Mechanical Data Menu

$$I^2 r = C_T \frac{d\theta}{dt} \quad (24)$$

where:	I^2r	is the input watts (conductor loss)
	C_T	is the thermal capacity of the conductor in watt-sec./°C
	$d\theta/dt$	is the rate of change of temperature in °C/second

The equation can be integrated to find the temperature rise:

$$\theta = \frac{1}{C_T} \int_0^t I^2 r \cdot dt \quad (25)$$

Therefore, for constant input watts:

$$\theta = \frac{I^2 r}{C_T} t \quad (26)$$

where θ is the temperature in °C

The heat equation can be represented as a current generator feeding a capacitor. In this analogy, the current is numerically equal to the watts, the capacitor equals the thermal capacitance, and the charge accumulated on the capacitor represents the temperature rise over ambient caused by the watts.

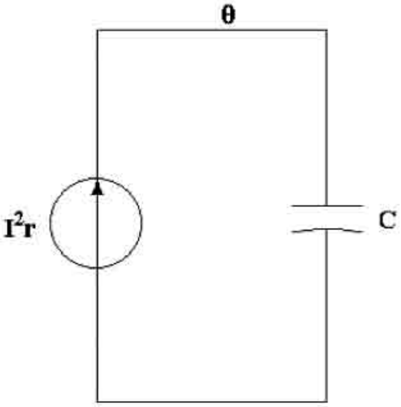


Figure 7: Electrical Analog Circuit

The temperature can be expressed in per unit and be plotted versus per unit current as a timecurrent characteristic. To do this let:

$$I = m \cdot I_{rated} \quad (27)$$

and substitute for I in equation (24):

$$\theta = \frac{(m \cdot I_{rated})^2 r}{C_T} t \qquad (28)$$

Divide equation (28) through by: $\frac{(I_{rated})^2 r}{C_T}$:

$$\theta \frac{C_T}{(I_{rated})^2 r} = m^2 t \qquad (29)$$

which can be written simply as:

$$U = m^2 t \qquad (30)$$

The above equations show that an I2t curve can represent a thermal limit. The curve represents a specific temperature expressed in seconds and is a straight line which has a slope of 2 when plotted on log-log paper.

If at locked rotor current ML, the thermal limit time is TA, then from (30) the temperature represents the rise over ambient:

$$U_L = M_L^2 T_A \qquad (31)$$

If at the locked rotor current ML, the time to reach the thermal limit is TO with the conductor initially at operating temperature, then equation (8) becomes:

$$M_L^2 T_A = M_L^2 T_O + U_O \qquad (32)$$

and the operating temperature in terms of ML, TA, and TO is:

$$U_O = M_L^2 (T_A - T_O) \qquad (33)$$

Equation (30) is the familiar I2t characteristic which plots as a straight line of slope 2 on log-log paper. The plot shown in Figure 8 represents a specific limiting temperature. The operating temperature, represented by Equation (33), is caused by one per unit current flowing in the thermal resistance of the conductor. Consequently, Equation (33) is the thermal resistance as shown in the electrical analog shown on Figure 9.

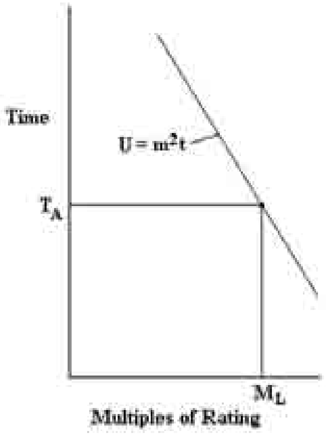


Figure 8: Time-Current Characteristic

THE MOTOR ANALYSIS

With the interactive electrical, mechanical, and thermal models defined by the input data, we can now relate the motor current, voltage, and rotor hot spot temperature to time during the start.

The plots are calculated by the program and displayed after specifying the parameters in the case menu shown in Figure 11. The plots are shown in Figure 12.

The plot is essentially an oscillogram of the starting condition. Analyzing the plot we can see that assigned WR2 gives the approximate starting time and that temperature, U, reaches only 0.615 per unit of the thermal limit. The relay response indicates an adequate relay coordination margin. A program option displays a log-log plot of the SEL-501 characteristics shown in Figure 13 and automatically calculates the settings as shown in Figure 14.

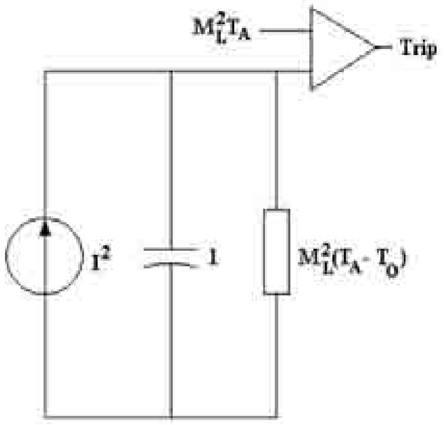


Figure 9: Electrical Analog With Thermal Resistance

CONCLUSIONS

The parameters chosen to supplement the motor nameplate data allowed us to verify the known motor voltage and accelerating time. The study determined an adequate relay coordination time when the proper relay thermal protection characteristic is applied. The trace of the starting current verified that the existing moderately inverse relay, set for 14 seconds at locked rotor current, lacked the coordination time for the long duration reduced voltage start.

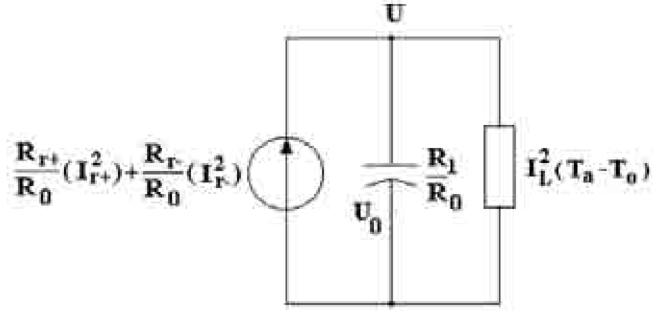
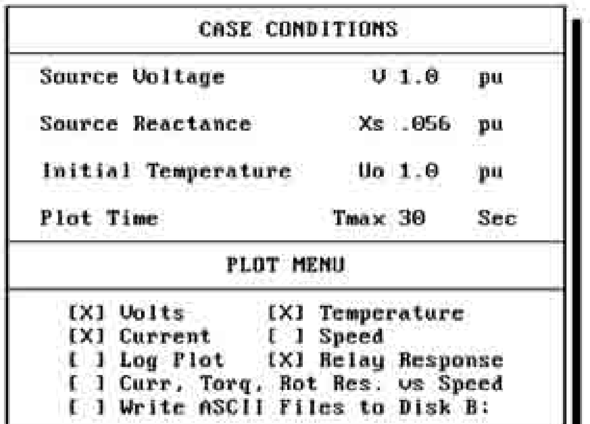


Figure 10: Motor Thermal Model



```
CASE CONDITIONS

Source Voltage           V 1.0    pu
Source Reactance        Xs .056   pu
Initial Temperature     Uo 1.0    pu
Plot Time             Tmax 30     Sec

PLOT MENU

[X] Volts        [X] Temperature
[X] Current      [ ] Speed
[ ] Log Plot     [X] Relay Response
[ ] Curr, Torq, Rot Res. vs Speed
[ ] Write ASCII Files to Disk B:

OK
```

Figure 11: Case Menu

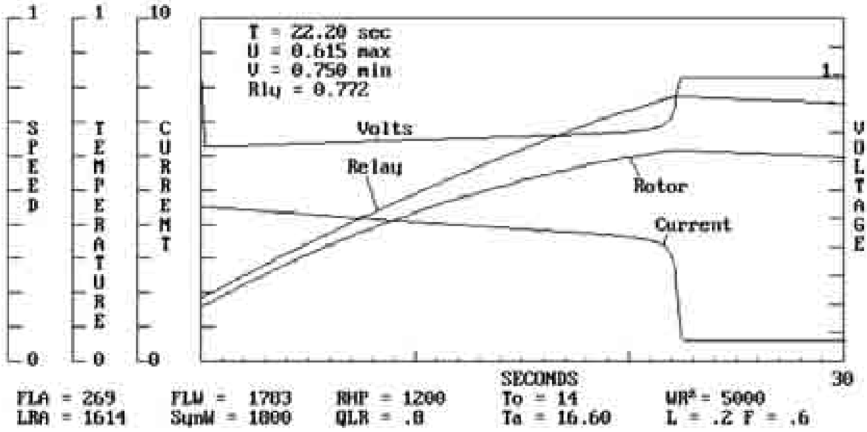


Figure 12: Plot of Motor Voltage, Current, and Rotor Hot Spot Temperature

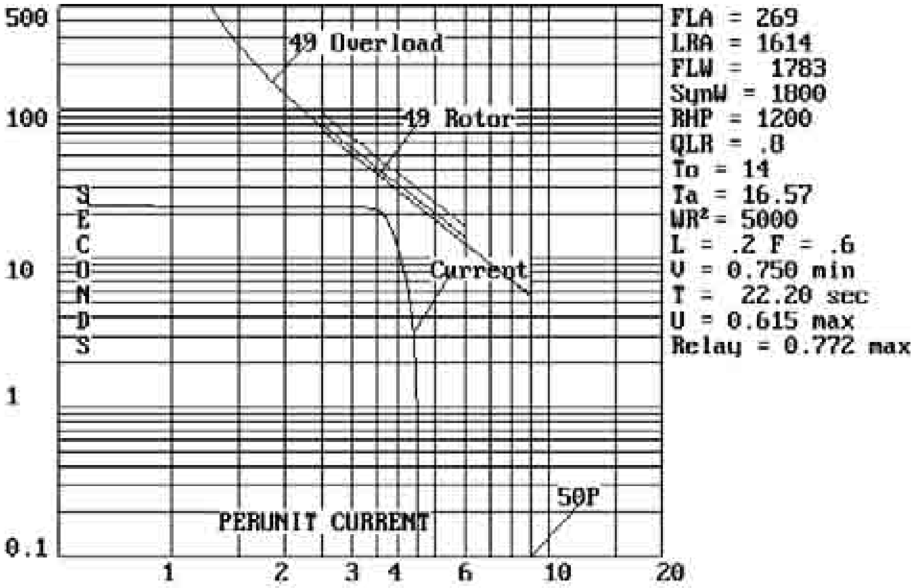
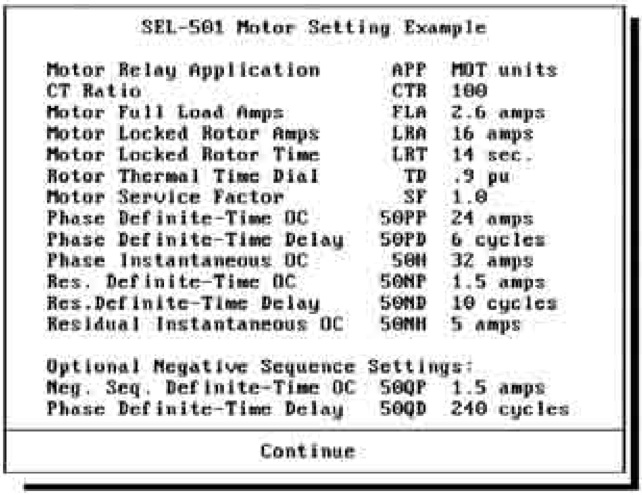


Figure 13: Log Plot of Current and SEL-501 Characteristic



```
                SEL-501 Motor Setting Example

  Motor Relay Application        APP   MOT units
  CT Ratio                       CTR   100
  Motor Full Load Amps           FLA   2.6 amps
  Motor Locked Rotor Amps        LRA   16 amps
  Motor Locked Rotor Time        LRT   14 sec.
  Rotor Thermal Time Dial         TD   .9 pu
  Motor Service Factor            SF   1.0
  Phase Definite-Time OC        50PP   24 amps
  Phase Definite-Time Delay     50PD   6 cycles
  Phase Instantaneous OC         50H   32 amps
  Res. Definite-Time OC         50NP   1.5 amps
  Res.Definite-Time Delay       50ND   10 cycles
  Residual Instantaneous OC     50NH   5 amps

  Optional Negative Sequence Settings:
  Neg. Seq. Definite-Time OC    50QP   1.5 amps
  Phase Definite-Time Delay     50QD   240 cycles
```

Figure 14: Motor Relay Settings

INDUCTION MOTORS: PART II - PROTECTION

THERMAL PROTECTION

Manufacturers of motor relays have used RTDs to try to protect motors from thermal damage.

Unfortunately, the slow response of RTDs reduces their value. Users must instead rely on inverse time-phase overcurrent elements and a separate negative-sequence overcurrent element to detect currents that could lead to overheating. Neither time overcurrent protection nor RTDs account for thermal history or accurately track the excursions of conductor temperatures.

An element should be used that accounts for the slip dependent I2r heating of both positive- and negative-sequence current. The element is a thermal model, defined by motor nameplate and thermal limit data. This mathematical model calculates the motor temperature in real time. The temperature is then compared to thermal limit trip and alarm thresholds to prevent overheating from overload, locked rotor, too frequent or prolonged starts, or unbalanced current.

What data defines the thermal model? Full load speed, the locked rotor current and torque, and the thermal limit time define it. What does torque have to do with the thermal model?

The I2r heat source and two trip thresholds are identified by the motor torque, current, and rotor resistance versus slip shown in Figure 1. It shows the distinctive characteristic of the induction motor to draw excessively high current until the peak torque develops near full speed. Also, the skin effect of the slip frequency causes the rotor resistance to exhibit a high locked rotor value labeled R1 which decreases to a low running value at rated slip labeled R0.

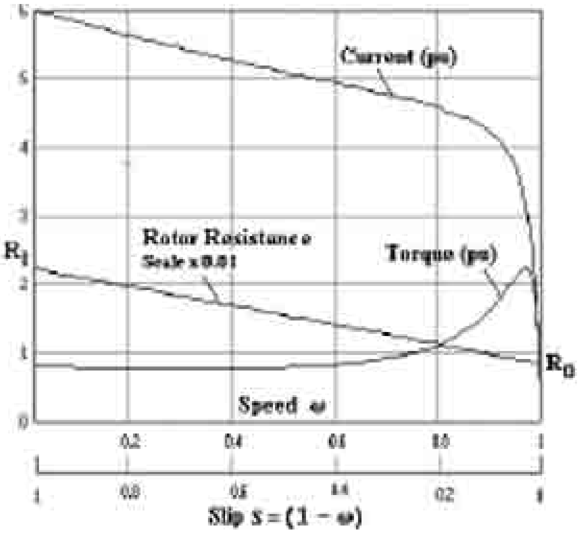


Figure 1: Current, Torque, and Rotor Resistance of an Induction Motor Versus Speed

A typical starting current of six times the rated current and a locked rotor resistance R1 of three times the value of R0 causes the I2r heating to be 62 x 3 or 108 times normal. Consequently, an extreme temperature must be tolerated for a limited time to start the motor. A high emergency I2t threshold is specified by the locked rotor limit during a start, and a second lower threshold for the normal running condition is specified by the service factor. Therefore, the thermal model requires a trip threshold when starting, indicated by the locked rotor thermal limit, and a trip threshold when running, indicated by the service factor.

How is the heating effect of the positive- and negative-sequence current determined?

The positive-sequence rotor resistance is plotted in Figure 1 and is calculated using current I, torque Q_M, and slip S in the following equation:

$$R_r = \frac{Q_M}{I^2}S \qquad (1)$$

It is represented by the linear function of slip shown in Figure 1. The positive-sequence resistance R_r+ is a function of the slip S:

$$R_{r+} = (R_1 - R_0)S + R_0 \qquad (2)$$

The negative-sequence resistance R_r- is obtained when S is replaced with the negative-sequence slip (2-S):

$$R_{r-} = (R_1 - R_0)(2 - S) + R_0 \qquad (3)$$

Factors expressing the heating effect of positive- and negative-sequence current are obtained by dividing Equations 36 and 37 by the running resistance R0. Consequently, for the locked rotor case, and where R1 is typically three times R0, the heating effect for both positive- and negative sequence current is three times that caused by the normal running current.

$$\left.\frac{R_{r+}}{R_0}\right|_{S=1} = \left.\frac{R_{r-}}{R_0}\right|_{S=1} = \frac{R_1}{R_0} = 3 \qquad (4)$$

For the running case, the positive-sequence heating factor returns to one, and the negative sequence heating factor increases to 5:

$$\left.\frac{R_{r+}}{R_0}\right|_{S=0} = 1 \quad \left.\frac{R_{r-}}{R_0}\right|_{S=0} = 2\left(\frac{R_1}{R_0}\right) - 1 = 5 \qquad (5)$$

These factors are the coefficients of the positive and negative currents of the heat source in the thermal model.

STARTING AND RUNNING STATES OF THE THERMAL MODEL

Because of its torque characteristic, the motor must operate in either a high current starting state or be driven to a low current running state by the peak torque occurring at about 2.5 per unit current. The thermal model protects the motor in either state by using the trip threshold and heating factors indicated by the current magnitude. The two states of the thermal model are shown in Figure 2. The thermal model is actually a difference equation executed by the microprocessor.

However, it can be represented by the electrical analog circuit shown in Figure 2.

In this analogy, the heat source is represented by a current generator, the temperature is represented by voltage, and thermal resistance and capacitance are represented by electrical resistance and capacitance. The parameters of the thermal model are defined as follows:

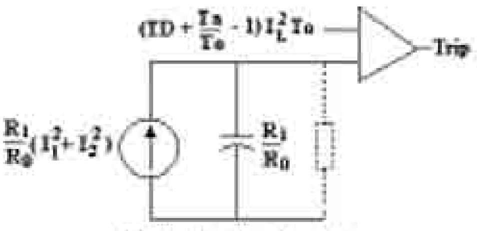
R1 = Locked rotor electrical resistance (per unit ohms)

R0 = Running rotor electrical resistance also rated slip (per unit ohms)

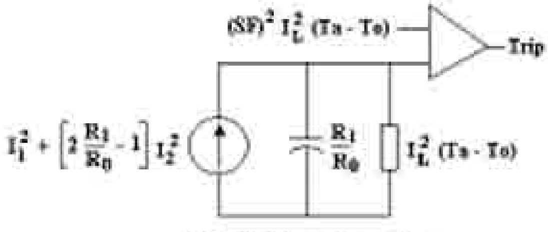
IL = Locked rotor current in per unit of full load current

Ta = Locked rotor time with motor initial at ambient

To = Locked rotor time with motor initially at operating temperature


$(TD + \frac{Ta}{To} - 1) I_L^2 To$
Trip
$\frac{R_1}{R_0}(I_1^2 + I_2^2)$
$\frac{R_1}{R_0}$

(a) Starting State I > 2.5 pu



(b) Running State I < 2.5 pu

Figure 2: States of the Thermal Model

The starting state is shown in Figure 2a and is declared whenever the current exceeds 2.5 per unit of the rated full load current and uses the threshold and heating factors derived for the locked rotor case. Thermal resistance is not shown because the start calculation assumes adiabatic heating. The running state, shown in Figure 2b, is declared when the current falls below 2.5 per unit current and uses the heating factors derived for the running condition. In this state, the trip threshold "cools" exponentially from a locked rotor threshold to the appropriate threshold for the running condition using the motor thermal time constant. This emulates the motor temperature which cools to the steady state running condition.

In the model, the thermal limit $I_L^2 T_a$ represents the locked rotor hot spot limit temperature and $I_L^2 (T_a - T_o)$ represents the operating temperature with full load current. The locked rotor time T_a is not usually specified but may be calculated by using a hot spot temperature of six times the operating temperature in the following relation:

$$\frac{I_L^2 T_a}{I_L^2 (T_a - T_o)} = 6 \therefore \frac{T_a}{T_o} = 1.2 \qquad (6)$$

There are two reasons for using the rotor model in the running state. The first is that the rotor model accounts for the heating of both the positive- and the negative-sequence current and conserves the thermal history at all times throughout the starting and running cycle. The second is that it is an industry practice to publish the overload and locked rotor thermal limits as one continuous curve as illustrated in Figure 3. Figure 3 is the time-current characteristic of the thermal model plotted with the motor initially at ambient temperature. Despite the difference in input watts and thresholds, the characteristics of the running and starting states plot as a continuous curve. This condition occurs when the locked rotor threshold is set at 0.8 of I_L^2 - Ta, and the motor service factor is 1.2.

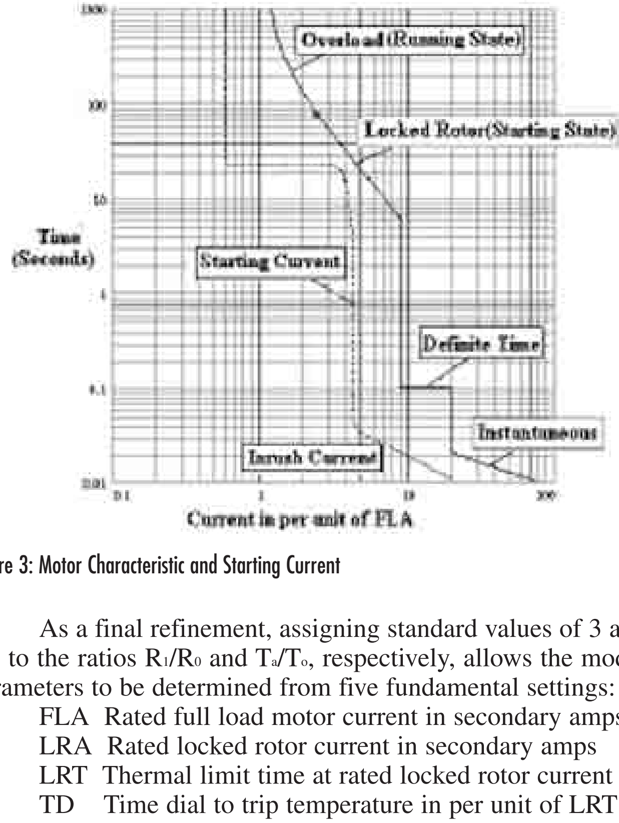


Figure 3: Motor Characteristic and Starting Current

As a final refinement, assigning standard values of 3 and 1.2 to the ratios R_1/R_0 and T_a/T_o, respectively, allows the model parameters to be determined from five fundamental settings:

FLA	Rated full load motor current in secondary amps
LRA	Rated locked rotor current in secondary amps
LRT	Thermal limit time at rated locked rotor current
TD	Time dial to trip temperature in per unit of LRT
SF	Motor rated service factor

The thermal circuit derived in this paper and shown in Figure 2 is covered by U.S. Patent No. 5,436,784.

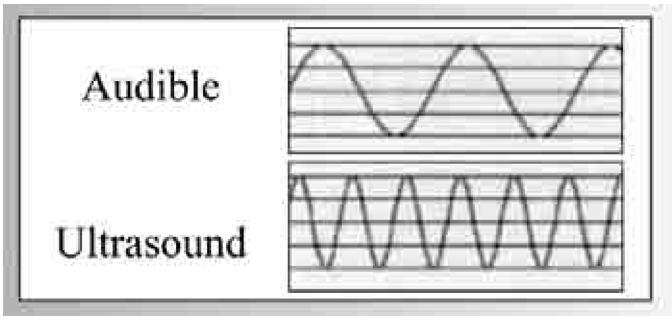
FAULT PROTECTION

In addition to the thermal element described above, definite-time and instantaneous phase and ground elements provide protection for faults in the motor leads and internal faults in the motor itself. The characteristics of these elements are plotted in Figure 3. A definite-time setting of about 6 cycles allows the pickup to be set to 1.2 to 1.5 times locked rotor current to avoid tripping on the initial X_d” inrush current (shown magnified). The instantaneous element is set at twice the locked rotor current for fast clearing of high current faults. Similar definite-time and instantaneous elements provide for ground fault protection.

APPLYING ACOUSTIC VIBRATION MONITORING TO PREDICTIVE MAINTENANCE

Allan Rienstra and James Hall, SDT North America

WHAT IS ULTRASOUND?



SOUND VS. ULTRASOUND

All sounds are produced by vibrations in bodies. In musical instruments the sound is emitted by vibrating strings or a reed. Our voice is the result of vibrations of our vocal cords. The number of vibrations a body makes per second is called its frequency and is commonly referred to as hertz.

Ultrasound is defined as "…sound waves having a frequency above the limits of human hearing, or in excess of 20,000 cycles per second (hertz)". So, by definition, ultrasound is totally undetectable by human ears unless aided by instruments capable of translating ultrasound to audible sound. In the marketplace, these instruments are commonly known as ultrasonic detectors and have been used for various maintenance related functions for over 25 years.

SOUND PROPAGATION THEORY

Sound is propagated by longitudinal waves through virtually any medium (air, water, glass, metal, etc…). A wave is a moving disturbance that causes the particles of the medium through which it is passing to vibrate. In such waves, the particles over which the wave is passing are made to vibrate in a line parallel to the direction in which the wave is moving.

PROPERTIES OF ULTRASOUND

The energy of a sound wave diminishes the further it travels from its source. Because sound waves spread out in widening spheres their energy is dispersed over a large area. This phenomenon is known as attenuation. Audible sound will propagate further and wider than ultrasound with the same energy, because an audible sound wavelength is much longer than an ultrasound wavelength. For this reason ultrasound is more directional to its source than lower frequency audible sounds. This directional characteristic makes it easy to pinpoint the exact source of the ultrasound even in very loud and noisy environments (like your plant floor).

HOW ULTRASONIC DETECTORS WORK

If we want to listen to ultrasound, we need an instrument capable of translating high frequencies into a range we can hear (normally 200-5000 hertz is a comfortable listening range). That is the function of an ultrasound detector. If we want to listen ONLY to ultrasound we need a detector with certain filters to eliminate audible or "parasite" noises. If we want to measure the energy of the ultrasound then the detector should have digital measurement capabilities. This equipment can usually store the measurements to an onboard memory chip and transmit the data to PC software.

TYPES OF SENSORS

Ultrasonic detectors use sensors with piezo-electric quartz crystals which are excited by the energy of certain ultrasonic vibrations. These vibrations are sensed by the detector and translated from their high frequency state to a low frequency state. The sound quality is maintained during this translation so the ultrasound is clearly heard in a headphone.

Sensors are designed to receive both airborne and structure-borne ultrasound.

TREATMENT AND MEASUREMENT OF SIGNAL

Ultrasonic or acoustic vibration is energy created by the friction between moving components (bearings, couplings, gear mesh, etc…). This energy is really an AC voltage or current that is at best, highly unstable and erratic. To provide useful data for acoustic vibration monitoring this energy must be made linear for repeatability purposes.

A quality ultrasonic detector uses True RMS conversion techniques to accomplish this. RMS means "Root Mean Squared". It's a way of measuring an AC voltage by means of taking the root of mean squared samples. Basically, True RMS measurement is a technique that provides consistent theoretically valid measurements of electrical signals derived from mechanical phenomena such as strain, stress, vibration, shock, expansion, bearing noise, and acoustic vibration. The electrical signals pro-

duced by these mechanical actions are often noisy, non-periodic, non-sinusoidal, superimposed on DC levels, and require True RMS for, valid, accurate, and repeatable measurements.

ACOUSTIC VIBRATION MONITORING

WHAT IS ACOUSTIC VIBRATION MONITORING?

Bearings, good or bad, new or old, produce ultrasonic friction as the internal rolling elements turn against the inner and outer raceway. A good bearing will produce less acoustic energy than a bearing with typical wear flaws such as pitting, spalling, flattening of the balls, and scarring of the raceway. Likewise, the friction absorbing properties of grease means a well-lubricated bearing produces less friction than a bearing that lacks lubrication. As the lubricant's viscosity deteriorates, and/or the bearing's material composition stresses and fatigues, the friction and the corresponding ultrasonic emissions increase. Monitoring and trending high frequency bearing energy allows us to determine proper lubrication intervals and predict when the bearing enters its FIRST stages of wear.

ACOUSTIC VIBRATION MONITORING VS VIBRATION ANALYSIS

Ultrasonic inspection must not be confused with low frequency vibration analysis. Low frequency vibration measurements (velocity or displacement) indicate a bearing in an advanced state of wear and provide information about root cause of premature failure (misalignment, imbalance, etc…). Normally there is a smaller window of opportunity to schedule downtime since the bearing is already advanced to a failure state. High frequency acoustic vibration monitoring controls the evolution of the bearing, indicates necessary lubrication intervals, and triggers alarms before the bearing enters failure state.

The earliest indication of change means corrective action can be taken quickly to increase the machine's longevity. If one goal of predictive maintenance is to extend the lifespan of production machines, then monitoring acoustic vibrations must play an integral role.

Remember that ultrasonic inspection controls and trends the evolution of bearing wear. It should not be considered a replacement for vibration analysis, rather an enhancement to any good vibration based predictive maintenance program.

Because of the relative low cost of ultrasonic detection equipment, this technology is also an excellent choice for small and medium sized companies with smaller budgets dedicated to capital equipment.

TRENDING BEARING WEAR WITH ULTRASONIC DETECTION

ESTABLISH A ROUTE-BASED METHOD OF DATA COLLECTION

Today's ultrasonic instruments allow greater flexibility than instruments from only a few years ago. Smaller, more powerful electronic components allow for complex data storage and two-way communications with PCs. Proper acoustic vibration monitoring means establishing a route-based method of data collection similar to that of your vibration routes. Establish routes or groups of machines in a logical sequence and identify asset names to each measurement point for storage, trending, and time-based graphical representation of bearing condition.

MEASURED VALUE (DBMV) AND ITS CORRELATION TO CONDITION

At the outset, the goal is to establish a baseline or normal operating range for each bearing to be checked. Throughout the life of a bearing, its ultrasonic level should remain relatively constant (+/- 3 or 4 dBmV). As the condition of the bearing changes, increases in acoustic energy due to either lubrication breakdown or structural breakdown will be observed. Increases correspond with an elevated reading (dBmV) on the instrument. Trending acoustic energy with data logger software allows the user to accurately predict when lubrication should be applied to a bearing, and when the bearing itself is entering early failure stages.

Remember, trending acoustic vibration warns us of the earliest signs of change in a bearing. Diligent use of the information gathered results in better lubrication practices and extended bearing life. The desired result is a much larger window through which to schedule repairs and change outs.

To optimise ultrasonic inspection techniques, it is essential to listen to the bearings; not just read the values on the display.

Listening to the ultrasound of a bearing provides significant qualitative information that correlates to the measured values. A low, muffled smooth noise associated to stable values indicates a normal functioning bearing. A strident high-pitched noise indicates a lack of lubrication, an overload or a rotation speed beyond spec of the bearing. A crackling noise associated to unstable or high dB values indicates faults, wear or loose metal particles in the lubricant.

Ultrasonic detectors provide an excellent quantitative measurement via the digital display, but do not ignore the qualitative information provided by the headphone output.

ULTRASOUND DETECTION FOR YOUR LUBRICATION PROGRAM

Lubricant absorbs energy created by friction between the rolling elements of a bearing. Acoustic vibration is low when the bearing is properly lubricated but as the lubrication film

breaks down this energy logarithmically increases; even though the bearing may not have any significant wear.

An increase of 8 to 10 dBµV over historical baseline indicates a need for lubrication. This is confirmed by listening to the bearing's acoustic qualities in the headphones, or by viewing the waveform on a spectrum analyzer. Bearings lacking lubrication will sound louder, with a rough growl, compared to the relatively smooth whirring noises of a well-greased bearing. The waveform on an oscilloscope will show inconsistent peaks if the bearing is lacking grease.

ULTRASONIC DETECTORS CAN TELL US WHEN TO STOP GREASING

An ultrasonic detector tells us when it's time to grease, and also when it's time to stop greasing. Some ultrasonic detectors offer a lube adaptor that attaches an ultrasonic contact sensor to any standard grease gun to permit listening and lubricating simultaneously. While listening to the bearing's sound quality in the headphones, begin pumping the grease gun, giving only one half* pump at a time. The sound quality changes as the grease reaches its intended destination.

Re-take the dBuV measurement and compare. You will notice a change in amplitude once the grease reaches the bearing. Stop greasing. Re-take the dBuV measurement and compare. In most cases, the sound level or dBuV will be lower than the original baseline. Again re-take the reading and store the new baseline for future reference. If, after the initial half pump of grease you notice an increase in the sound level stop lubricating and wait 10-15 seconds for the sound ultrasound level to stabilize. If it does not stabilize or decrease, stop lubrication of the bearing.

*A grease gun is capable of producing 150 to 200 pounds per square inch of pressure. For this reason, we caution against ever using a full pump of grease to avoid over lubrication and creating unnecessary damage to the bearing, seals, and motor.

If too much grease is applied, the overage may enter the motor and cause a short, leading to a motor failure. In our experience, you will hear a slight increase while lubricating (it may be after one or two, half pumps of grease). Some time may have to pass for the increase to settle down or lower. If it does not settle down, stop lubricating. The balls may be pushed up against the raceway due too much grease being applied. By using half pumps with the grease gun instead of full pumps, we are trying to avoid this pressure build-up. In most cases, using the half pump method and listening with ultrasound will avoid over lubrication.

We suggest that this be done to all critical motors at least once, and all other critical bearings that are not read by vibration because of slow speed or accessibility.

CONCLUSIONS AND SUMMARY

The goal of any predictive maintenance program should be to arm yourself with tools that give you the best information to make an informed decision on the condition of your plant's production machinery. Ultrasonic detection enables us to hear the earliest signs of machine failure and lubrication breakdown; normally with a large enough window to act within the confines of a planned shutdown. Ultrasonic inspection is an excellent stand-alone technology for all maintenance departments wanting to start or enhance a vibration monitoring program. Vibration analysts will also reap immediate benefits by implementing acoustic vibration monitoring techniques to enhance their existing vibration routes. The more "good" information we can give ourselves, the better able we are to make the right decision about the relative health of our production machines.

MOTOR DESIGNS TO SURVIVE HOSTILE ENVIRONMENTS

Rick Halstead, President of Empire Magnetics, Inc.

A new generation of step motors is allowing motion control applications to prosper where they were previously impossible or, at best, very difficult. The reason? Previous step motor designs were developed for the relatively “benign” conditions in a factory. New step motor designs - specially developed for motor-hostile environments - can reliably withstand the effects of radiation, underwater operation, vacuum operation, and extremely high and low temperatures, among other conditions. Accordingly, these motors are the key to a wide range of new motion control opportunities.

VACUUM MOTORS

The problems inherent in operating a motor in a vacuum - outgassing, contamination and temperature - are well known to design engineers. Solutions are less well known.

Common requirements for vacuum operation include the ability to accurately move or position samples, products, mirrors and sensors. In the past, this has often been accomplished by trying to evade the effects of the vacuum, by locating drive mechanisms and motors outside the vacuum chamber. The drive mechanism transmits its motion through the vacuum chamber wall using sealed couplings and magnetic or mechanical feedthrough mechanisms.

One major problem with this approach is that the engineer has a limited number of design configurations he can consider. It can be very difficult to implement an X-Y stage (in which one stage moves on top of the other) inside a vacuum area when motors are outside the chamber, since the mechanisms used to transfer motor power to the top stage must also accommodate the motion of the bottom stage. The accuracy, repeatability, and resolution of the positioning system located inside the vacuum chamber can be heavily compromised.

In contrast, placing the motor directly into the vacuum allows the engineer to consider a larger number of physical design arrangements without compromising the motion control activity inside the chamber. By directly coupling the motor to the load, the accuracy, repeatability and other system specifications can be vastly improved. Because mechanical feedthroughs are very expensive, a system that features an internally-placed motor often costs much less than the externally-mounted alternative.

Ordinary motors will not survive in a vacuum application of 10-4 Torr or lower. The reason is that the bearing lubricants will vaporize and the motor’s and cable’s insulation materials will evaporate in a phenomenon that is known as “outgassing”, resulting in destruction of the motor. Outgassing further results in vaporized materials condensing on any precision optical components or delicate mechanical devices that are present. Among other materials commonly found in a standard motor, bearing grease, paper slot liners, conformal coatings, winding insulation, and many kinds of adhesives vaporize in a vacuum.

Some materials are particularly inappropriate for a vacuum chamber, since they outgas so quickly that clouds of vapor are created. Other materials, such as silicone, are an even bigger problem: silicone is nearly impossible to remove by cleaning, and will continue to spread throughout the chamber, contaminating its contents.

Air leaking from the motor itself is another frequent problem with vacuum motor operation. A step motor that has not been adequately prepared will leak air molecules long after the vacuum is applied. Captured or clinging gas molecules slowly emanate from minute cracks in the motor laminations, windings, bearings and metal surfaces. If these porous materials are not treated, an unacceptably long pump-down time or inadequate vacuum level can result.

Motor cooling in vacuums is another problem. Standard motors are generally cooled by convection into the surrounding air and, less significantly, by heat conduction through the motor mounting surface. Convection cooling is not available in a vacuum. Heat is dissipated mainly by the least-efficient method: conduction through the mounting structure. As a result, vacuum operation can require special cooling devices and higher temperature operation.

Finally, corona effects can result from exposed high voltage conductors. At certain vacuum levels, the rarified air ionizes easily, and current can arc between unprotected high voltage conductors.

Solutions to all of these vacuum motor problems - outgassing, cooling, leakage, and corona effects - have been answered by new designs in vacuum motors. Outgassing, for example, can be prevented by the selection of materials with low vapor pressure. Teflon is one such stable material. Most metals are also suited to use in a vacuum (exceptions include cadmium and zinc). Stainless steel is a particularly good material for vacuum applications.

Material outgassing rates are generally not significant between atmospheric pressure and 10-4 Torr. In this range, many commercial plastics are usable, although lubricants usually need to be selected carefully. In vacuums approaching 10-7 Torr, most natural materials must be eliminated in a motor, few plastics are viable, and vacuum lubricants are mandatory. At 10-9 Torr, almost no plastics can be used, and dry lubricants are required.

Scrupulous motor cleaning limits outgassing problems. Trace materials from the motor manufacturing process are always present from a variety of sources: cutting oils are used on steel, lubrication is left on plastics when extruded from dies, and solvents are mixed with epoxies. Human hands leave an oil residue behind. Outgassing contamination is not critical in all applications, but if system components are not properly cleaned, outgassing of various contaminants will definitely result.

Manufacturers that specialize in motors for vacuum environments, such as Empire Magnetics, subject motors to a cleaning process that gets into crevices that vapor degreasing cannot access, accelerating molecular changes in materials that would otherwise outgas, making them inert. The sensitivity of vacuum applications usually requires the use of motors that have been constructed of non-volatile materials, vacuum baked, processed to extract contaminants, and then sealed.

Recent Step Motor Vacuum Applications:

- Satellite testing/positioning of satellite in vacuum chamber during assembly;
- Observatory instrumentation/telescopes;
- Alignment of laser beams for research;
- Beam alignment during fusion research;
- Semiconductor manufacturing;
- Wide range of clean room applications for research and testing;
- Aircraft component testing;
- Superconductor research;
- Ion deposition equipment;
- Electron beam welders;
- Electron microscopes;
- Material testing facilities.

Remedies for high motor temperatures include limiting power to the motor, and fabricating the motor with high temperature materials. A thermocouple or RTD (resistance thermometer device) can be installed in the motor to monitor temperature. The temperature information is used to modulate motor power, in order to keep the temperature within a safe operating range. When substantial amounts of power must be applied, cold plates or cooling jackets can be considered. For one example, Hughes Aircraft designed and installed a system that used the vapor from liquid nitrogen and which was controlled by a feedback system that monitored motor temperature. Even though the motor was heavily loaded for three months of continuous satellite testing, this system reliably held the temperature to a safe level.

Finally, to prevent the corona effect that can be generated by high voltage, exposed conductors must be insulated with appropriate coatings to prevent arcs.

WATERPROOF STEP MOTORS

Because of the preponderance of water and solvents, motion control components are often exposed to the risk of corrosion and failure. Waterproof motors are a key part of the solution to water-induced motor failure problems.

Today's waterproof motors are specifically designed to survive a minimum of 30 feet under the sea, a general industrial standard for the "waterproof" designation. These are not retrofitted standard step motors, but are truly waterproof motors, which operate very well above the waterline, too - in a wide variety of industrial and marine settings. The motors have been fitted with redundant shaft seals, O rings, hermetic cable feedthrough, pressure equalization and other waterproofing features. Together, these design features allow a step motor to answer a design engineer's need for a motor that will not fail even after prolonged exposure to, or submersion in, most liquids.

Why don't ordinary step motors meet this need? Although these motors are the mainstays of industry and the laboratory, and provide reliable and accurate positioning for minimal cost, their design includes several weaknesses with respect to moisture. First, the coils of the standard stepper are wound with magnet wire, a solid copper wire that is coated with an enamel or varnish. While the coating process is good, it is not perfect, and the varnish always has some small pin holes in it.

When this magnet wire is wound into a coil, it is unlikely that any two pin holes will line up and "short out". Ordinarily, the spacing of the wires provided by the layers of exterior enamel prevent conduction from one pin hole to the next. However, if even a little water gets between the wires, it will promote conduction from pin hole to pin hole. In this situation, the current from the power supply will quickly destroy the motor windings. Although quality insulation and impregnation can prevent this problem, they add greatly to product cost.

Step motors are constructed of magnetic iron, and corrode very easily when subjected to moisture. To optimize torque, the gap between the rotating and non-rotating teeth of the motor is held to about .002 in. When the motor is operating, these teeth get hot, and the temperature is typically high enough to turn any water in the motor into steam. Steam is corrosive, such that the magnetic iron in the teeth rusts faster than usual.

Once the rust fills the .002 in. air gap, rotor and stator teeth begin to rub. This robs useful torque from the motor and breaks the iron oxide loose. If the rust is dry, it forms an abrasive powder, if it is wet, it forms an abrasive slurry. This oxide slurry gets into the motor bearings, and being abrasive, the bearing wear accelerates. As the bearings wear, the centering of the rotor becomes less accurate, causing the rotor to wobble as it turns and eventually hit the stator.

The combination of oxide build-up on the magnetic teeth and the loss of bearing accuracy can cause a standard step motor to fail in a period as short as two weeks. While it is possible to substitute non-corrosive metals for the magnetic iron, the metal will be more expensive, it will cost more to machine, and motor performance will be significantly degraded.

Attempts could be made to prevent moisture from entering a motor. However, standard step motors are not designed to facilitate seals. They are designed to be low in cost. As a result, proper sealing of the motor would require a complete re-design of motor parts, with an increase in manufacturing cost.

A proper design approach for motors exposed to moisture incorporates shaft seals, O rings, cable feedthrough, and pressure equalization mentioned earlier with other features that combine to create a "real" waterproof motor. For instance, while standard motor housings are made of painted cold rolled steel and/or aluminum, a waterproof motor's exterior is commonly made of stainless steel to resist corrosion.

A waterproof motor is designed to accommodate O-ring seals, allowing the watertight sealing that is not practical in a standard motor. Further, the wiring that leads to the motor coils in a waterproof motor requires a hermetically-sealed feedthrough device to prevent water from wicking into the motor via the cable conductors.

Other seals are required. For instance, a threaded pipe plug at the rear of the motor is designed to allow the housing to be sealed after the motor connections have been made; this plug is also fitted with an O-ring seal. The motor shaft itself is provided with redundant shaft seals. Additional life-extending features include double insulation, coated laminations, and fittings for pressurization.

Some of the above features may be found on a standard motor, but it is the combination of all of these features together that produces a waterproof motor with a superior service life.

The existence of the new waterproof motors, and the design innovations they represent, do not simply extend motor life in moisture-filled applications — in many cases, the applications would not be possible without this type of motor.

Recent Waterproof Step Motor Applications:

- Naval/military;
- Aquaculture;
- Undersea exploration;
- Robotic submarines;
- Salvage robots;
- Undersea mining;
- Oil exploration;
- Sonar arrays;
- Communications;
- Automated undersea lights and cameras;
- Automated hydrophone arrays;
- Wave power generation;
- Flood control systems;
- Floating seafood factories;
- Hydrofoil air cushion controls;
- Antenna and gun pointing systems;
- Food processing;
- Cleaning, chopping, dispensing, packaging, vacuum sealing, inspecting and labeling;
- Corn dog machines;
- Automated ice cream cup fillers;
- Meat slicers;
- Pineapple coring machines;
- Juice box filling and sealing machines;
- Drug manufacturing: Pill pack sealing, packing, labeling, gene splicing microscope stages, media plate filling;
- Medical supply manufacturing: Artificial blood vessels, rubber gloves, sterile bandages;
- Automated machine tools: Mills, lathes, screw machines, grinding applications, cut-off tools;
- Automated inspection: Water jets and ultrasound in water tanks, inspection of nuclear reactor components;
- Antenna pointing systems for satellite tracking stations;
- Upper atmosphere wind study equipment;
- Railroad track grinding equipment;
- Pipeline welding and pipeline x-ray equipment;
- Paper manufacturing;
- Chemical manufacturing;
- Film processing;
- Printing;
- Water jet cutting;
- Toxic clean-up equipment.

RADIATION-HARDENED STEP MOTORS

Motion control in radiation-intensive environments poses one of the most difficult design challenges possible to the engineer. Conventional step and microstepping motors are susceptible to high-energy gamma radiation particles that will attack non-metallic materials. As a result, lubricants, varnish, lamination bonding, and cable insulation will all deteriorate over time and finally crumble. Also, many radiation applications include additional environment problems, such as corrosive fluids.

Radiation-hardened step motors, however, have greatly expanded the design opportunities in highly radioactive environments. A recent motion control application at Oak Ridge National Laboratory (ORNL) in Oak Ridge, TN provides a good example of the possibilities created by these new designs, even in instances where there is more than one hostile condition in the environment.

Recent Radiation-Hardened Step Motor Applications:

- Fusion research;
- Material handling;
- Clean-up;
- X-ray machine;
- Fuel re-processing;
- Fast breeder reactor;
- Reactor inspection;
- Beam research.

RADIATION CASE HISTORY

An important step in the fuel recycling process is the separation of spent fuel oxides from their cladding by dissolving the oxides in nitric acid. ORNL, which is responsible for the development of nuclear fuel reprocessing technologies, recently developed a new concept for performing this separation process in collaboration with the Power Reactor and Nuclear Fuel Development Corporation of Japan (PRN).

The new concept devised by ORNL is a "multi-stage continuous rotary dissolver" that operates as a continuous, rather than batch-type, process. The new design provides a counter-current of nitric acid that is constantly forcing the highest acid concentrations against the hardest-to-dissolve areas of the fuel pins.

ORNL was able to find only one motor design that could withstand accumulated radiation dosages of 108 and which had all of the required performance specifications, a radiation-hardened hybrid permanent magnet step motor from Empire Magnetics. The Empire motor was a "zero backlash" model that features an in-line 87 to 1 cycloidal gear reducer, a design feature that increases motor output torque without lessening motor life. A radiation-hardened brushless resolver is connected to the gearbox output shaft. The resolver provided angular positioning capability with a resolution of 4,096 steps per revolution of the dissolver drum. The motor, gearbox and resolver were mounted inside a lead box to enhance the existing radiation resistance.

The key to a successful design for the ORNL project was in the proper selection of materials. Most critical was the specification of specific polymers, not only for magnet wire and cable insulation, but also for shaft and body seals. Finally, a heavy coat of radiation-resistant polymer paint provided the outer layer of defense against concentrated nitric acid vapor.

EXTENDED TEMPERATURE STEP MOTORS

Extended temperature step motor applications offer some particularly extreme operating conditions. As a satellite rotates in orbit, for instance, its motors experience incredible temperature swings as they move from the blazing sun (+200°C) to freezing shadow (-200°C) in a matter of seconds. Without a very specialized motor, there is no chance that the motor would operate through a 400° temperature cycle. Other applications can be just as hostile. In infrared observatory installations, where the positioning requirements are extremely precise, the motor and adjacent instrumentation may be cooled with liquid nitrogen. For superconductor experimentation, the system may be submerged in liquid helium (20° Kelvin!) and require a cryogenic motor design. In rocket applications, the motor may be pumping liquid oxygen. Of course, there are also high temperature applications that are just as hostile. One recent high temperature example is an automated remote throttle actuator for jet engine testing, which experiences temperatures over 100°C with extreme vibration and stringent safety requirements.

LOW TEMPERATURE MOTORS/CRYOGENIC MOTORS

Contraction of metallic parts and hardening of non-metallic parts are the two primary factors that can render a step motor non-functional in low temperatures. In the instance of contraction, if motor components with critical dimensions contract at different rates, a locked-up motor may result. The resultant stress can crack metal parts made brittle by super-cooling. To combat these effects, special alloys must be selected for a low temperature motor, and all metal components must have comparable coefficients of thermal expansion.

Both cable insulation and bearing grease are susceptible to hardening at cryogenic temperatures. Dry lubrication may be required and insulation polymers must be carefully selected to retain molecular integrity through low temperature cycling.

The following case history, which combined two separate hostile conditions in the application environment, represents a typical challenge faced by the design engineer working with a cryogenic application.

Recent Low Temperature Applications:

- Satellite controls;
- Antenna controls;
- Observatory instrumentation;
- Liquid oxygen pumping;
- Superconductor research;
- Plasma Processing;
- Frozen food handling;
- Paper mills;
- Steel forming;
- Metal coating.

Recent High Temperature Applications:

- Furnace operation;
- Industrial baking;
- Engine testing.

CRYOGENIC MOTOR CASE HISTORY

In a recent cryogenic application, engineers at Arnold Air Force Base were assigned to identify and qualify motors suitable for use in a vacuum chamber at cryogenic temperatures. The specification called for small motors operating in a vacuum of 10-7 Torr at liquid hydrogen temperatures (24o Kelvin). Angular position feedback was a requirement to accommodate closed loop velocity and position controls.

Two major design problems are inherent in this type of application. The first involves the outgassing of lubrication and insulation materials at low pressure. The second problem has to do with the behavior of motor materials at very low temperatures. The stress of large temperature changes, low temperature brittleness, and varying contraction rates of dissimilar materials work to degrade the structural integrity of motors manufactured from conventional materials.

A 57 mm diameter step motor was combined with a feedback resolver to meet the unique requirements of the application. Both devices were housed in an exotic nickel chromium steel alloy frame, selected for thermal stress resistance and dimensional stability. Resolver technology was selected for the feedback system due to the similarity of resolver components with those of the motor.

To reduce outgassing at low temperature, insulation materials were made of selected polymers. Magnet and lead wire materials were carefully specified to avoid outgassing or fracture. Bonding agents normally used to build the motors were replaced with adhesives having a coefficient of thermal expansion close to that of adjacent steel components.

Each of the metal components of the motor was examined in detail. AlNiCo (Aluminum Nickel Cobalt) magnets were selected in favor of rare earth combinations, since AlNiCo retains magnetic properties better at low temperatures. Stainless steel ball bearings, lubricated with dry film, were used for the same reason. All machined metal parts were stress-relieved. The result was a design that could operate at cryogenic temperatures and within the confines of a vacuum chamber without vaporization of motor materials.

HIGH TEMPERATURE MOTORS

At high temperatures, the principal failure mode is winding insulation failure and the resulting short circuit that occurs. To combat this problem, high temperature magnet wire rated to 180°C is commonly specified. Non-copper magnet wire that is protected with exotic insulation materials is used when the application involves temperatures over 200°C. Dry lubrication is used to avoid material loss.

A step motor isn't just a step motor anymore: more and more applications require that their inherent design reflect the operating conditions present. While these reliable motors are still the workhorse for many general motion control needs, their range has also extended into hostile application environments that have expanded their value, giving the design engineer a new "old" tool.

VARIABLE FREQUENCY DRIVES - ACHIEVING ENERGY EFFICIENCY AND MAINTAINING POWER QUALITY

Jeff Theisen, Sr. Drive Application Engineer, Rockwell Automation

As recently as a few decades ago, manufacturers assumed that energy costs were simply an uncontrollable cost. But such attitudes became outdated with the advent of variable speed drives and power-monitoring technologies capable of making energy a manageable expense – one that can be controlled by adjusting key processes to use less energy.

The ability to save energy today is considered a given in industrial settings, with tools and techniques to limit energy expenditures now including motor controllers, software and power monitoring and control devices capable of reducing energy costs and helping manufacturers control costs better than before.

Domestic manufacturers annually spend more than $33 billion on electricity, with motor systems consuming approximately 63 percent of all electricity. More than half of those motors are used in either fan or pump applications – key areas with phenomenal potential for energy savings. As a result, many manufacturers are looking for ways to reduce the power consumed for fan and pump applications.

FAN APPLICATIONS

As a rule, energy consumption in a fan or pump application varies by the motor's cube of speed, also called centrifugal load. For example, if the speed on a fan's motor can be decreased by half, the energy used to power the motor is actually decreased by 7/8. This equation, which also can be applied to pump applications, illustrates the point: (1/2) = 1/8

Most fan applications do not require the full amount of air movement that fans are designed to produce. So, to vary airflow, fan applications use methods such as:

- cycling (generally used in residential settings and not applicable in industrial settings),
- outlet dampers,
- variable inlet vanes and
- variable-speed drives.

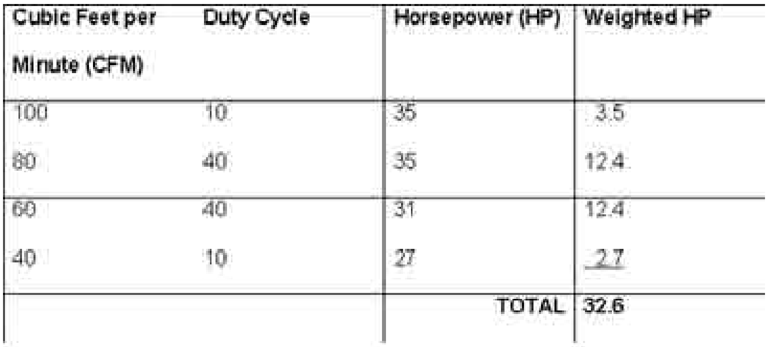
In industrial settings, variable-speed drives are generally the most effective means of controlling energy use because they control actual motor speed. Methods such as inlet vanes and outlet dampers only control the amount of air an application receives, not motor speed.

Charts 1 and 2 show the actual amount of energy used when controlling air flow using either outlet dampers (Chart 1) or variable speed drives (Chart 2). The figure in the right-hand box, "weighted horsepower," calculates the average horsepower used during a fan's on-off cycle, including the power needed to ramp up to speed and slow down.

Weighted horsepower is important, because it provides a glimpse into the amount of energy each motor uses to control air flow. Estimating power consumption and potential energy savings requires an actual load profile and a fan curve, both of which will vary over the course of fan operation (since fans need to ramp up to speed before operating at desired capacity).

The weighted horsepower of a fan is calculated by the percent of time a fan operates at a given power point. Calculations are summed to produce the weighted horsepower that represents the fan's average energy consumption.

Chart 1: Outlet Dampers



Cubic Feet per Minute (CFM)	Duty Cycle	Horsepower (HP)	Weighted HP
100	10	35	3.5
80	40	35	12.4
60	40	31	12.4
40	10	27	2.7
		TOTAL	32.6

Similar calculations can provide weighted horsepower figures for variable speed operations. However, because the fan curve does not have enough information to read all horsepower values for operating points, formulas from affinity laws need to be incorporated into the calculation.

The first point is obtained from the fan curve: 100 percent flow equals 100 percent speed, which equals 35 HP. The flow formula Q2/Q1 = N2/N1 can be substituted into the horsepower formula, $HP2/HP1 = (N2/N1)^3$ to give:

When Q1 = 100 percent and HP1 = 35 HP, Q2 and HP2 have the following values:

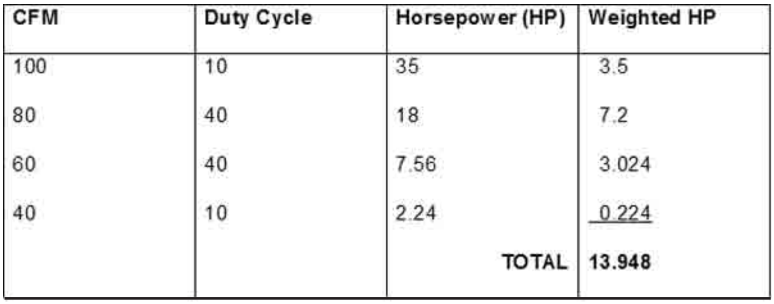
Example: (Q2/Q1)3 * HP1 = (80/100)3 * 35 = 17.92

Q2	80%	60%	40%
HP2	18	7.56	2.24

Sufficient information is now available to calculate weighted horsepower for variable speed operations.

In the examples outlined in Charts 1 and 2, we see that the outlet damper application has a weighted horsepower of 32.6, which is significantly higher than the variable speed drive's 13.948 weighted horsepower. In a hypothetical situation in which this same fan application is used 730 hours per month, with electricity costs averaging $0.07 per kWh, the dampered fan would incur more than $1,242 in energy costs. Meanwhile, the drive-controlled fan would use approximately $531 in electricity, representing a significant cost savings over the outlet damper system.

Chart 2: Variable Speed Drives



CFM	Duty Cycle	Horsepower (HP)	Weighted HP
100	10	35	3.5
80	40	18	7.2
60	40	7.56	3.024
40	10	2.24	0.224
		TOTAL	**13.948**

PUMP APPLICATIONS

Variable speed drives also can contribute to energy savings for pump applications. Controlling the speed of a pump is accomplished either through throttling the motor (mechanically changing the pump's speed) or employing a drive to control the motor's speed – and, therefore, the amount of energy used by the pump motor.

Just as certain calculations can show the energy savings possible in fan applications, similar calculations can be used to estimate energy savings for pumps. Generally, when pump speed is reduced by 20 percent from 100 percent, motor hp is reduced by nearly 50 percent, as is Brake HorsePower (BHP) – the indicator of how much energy a pump motor is using. BHP is equivalent to the power necessary to do the work at a particular speed divided by the motor efficiency.

For example, a motor/pump is running on a system across the line that flows 450GPM. However when the demand is only 225GPM the flow is reduced by partially closing a valve. According to a pump curve the pressure is increased from 180psf to 200psf, the efficiency is reduced from 76% to 60% and the horsepower requirement reduces from 30HP to 26HP. That same application on a variable speed drive would reduce the horsepower to 3.75.

Assuming a 225 GPM flow is required for 3000 hours a year at $0.07 per kWh, the comparison of costs for throttling versus a variable-speed drive system is dramatic:

Throttling:
26 HP x 0.746 = 19.396 kW
19.396 x 3000 = 58188 kWhr
58188 x $0.07 = $4073.16
Variable speed drive:
3.75 x 0.746 = 2.97 kW
2.97 x 3000 = 8392.5 kWh
8392.5 x 0.07 = $587.48
Savings:
$4073.16 - $587.48 = $3485.68 saving in energy costs using variable-speed drives

It's important to note that the above example assumes the pump system does not have a static head, or great resistance to flow, as is often associated with long pipes or pump length that rises significantly. The higher the resistance to flow, the lower the potential energy savings. Motor and drive efficiencies were also not considered.

In addition to taking advantage the Affinity Laws provide, additional benefits are relieving the stress on the mechanical system by not starting across the line vs. a drive ramping up to speed. Tighter process control can also be realized with the correct drive utilization.

HARMONICS AND POWER QUALITY

Power quality is an issue in all facilities that use large amounts of energy, including harmonics often associated with variable frequency drives.

Harmonics are deviations from the sinusoidal fundamental AC line voltage and current. While most electrical power in North America operates at a frequency of 60 hertz, a harmonic frequency operates at a multiple of its fundamental frequency. So, in a 60-hertz system, the second harmonic would be 120-hertz, the third would be 180-hertz and so on.

IEEE 519 ensures power quality by limiting the maximum current distortion caused by non-linear loads to limit the voltage distortion they would create, minimizing the likelihood of equipment failure due to the distortions. In other words, limiting the harmonics on electrical lines, both in and around facilities, improves power quality.

The addition of harmonics to the sinusoidal fundamental current or voltage creates distortion. The greater the amplitudes of harmonics present, the greater the distortion in the electrical waveform. What this means, very simply, is that whenever a voltage or current does not look like a perfect sinusoidal waveform, it contains harmonics.

Unlike an AC motor operating across the power line, the current drawn from a distribution transformer feeding a typical AC drive is far from a sinusoidal waveform. This occurs because the drive is taking current from the transformer only during certain times of the cycle to convert the AC line voltage to a fixed DC voltage within the drive. The drive then pulse-width modulates fixed DC voltage into variable-frequency voltage for the motor. The AC-to-DC conversion is what causes the harmonics. Current flows only during part of the cycle and is off during other parts of the cycle, creating an odd-looking current waveform. The distorted current creates voltage distortion.

Several methods and products can reduce line current harmonics created by drives. Even though the addition of line reactors or passive filters can help reduce the current harmonics, in some conditions they also will reduce the DC bus voltage within the drive in full-speed, full-load conditions. This will prevent the drive from being able to provide full power to the motor, limiting the power out of the motor to about 95 percent of its nameplate rating. Why install a 100-HP motor only to have its capability limited to 95 HP, especially under peak demand conditions? This is why multi-pulse solutions are a better fit for most situations; since no de-rating is necessary and such solutions are generally less expensive than other mitigation methods.

Manufacturers and users of industrial motors have more control over their energy costs today than they may realize. Likewise, power quality issues can also be mitigated with the technology that improves each year. Regenerative drives that put excess energy back on electric lines are available, and drives are being developed with more and more robust features, such as positioning capabilities. All of these features make drives an integral part of an energy savings program — far beyond the simple speed controllers they used to be.

INDUCTION MOTORS - CONSTANT FREQUENCY/VOLTAGE; VARIABLE FREQUENCY/VOLTAGE

Matthew Gonring, VP Global Marketing & Communications, Rockwell Automation

ABSTRACT

As more AC induction motors are applied to variable speed applications, it is increasingly important to understand how these motors operate. The differences between operation on "sinewave" power and "static" power supplies can be quite significant.

This session will review the basics of constant frequency/constant voltage operation of AC induction motors. These principles of operation will then be extended to the case of operation from variable frequency/variable voltage power. Finally, the effects of the non-sinusoidal voltage and/or current waveshapes will be covered.

INTRODUCTION

AC induction motors have for many years been reliable workhorses in converting electricity into rotating power. The last 20 years has seen increasing usage of these motors with adjustable frequency controls to add variable speed capability to AC motors. While AC motors were initially applied to relatively simple variable speed applications (such as varying the flow rate of a fan or pump), advances in AC motors and control technology have allowed their use in higher performance applications.

With these higher performance applications (and higher performance motors and controls) has come the need for "high performance" matching of the control, motor, and the application. This session will provide additional understanding of the adjustable-frequency, variable-speed operation of AC induction motors, with the intent of fostering "smarter" application and improved performance.

CONSTANT FREQUENCY, CONSTANT VOLTAGE OPERATION TERMINOLOGY AND EQUIVALENT CIRCUITS.

Before trying to understand the operation of AC induction motors on adjustable-frequency power (variable-speed), it will be useful to briefly review the basic fixed-frequency operation of AC induction motors. The fundamental electromagnetic components are the stator and rotor (Figure 1). In the most common configuration, the stator has three interconnected phase windings, and the rotor winding is a set of short circuited bars known as a "squirrel cage."

With balanced three-phase voltages applied to the windings of the stator, balanced currents flow in the three interconnected phase windings. These currents produce a magnetic field which "rotates" within the stator at a speed given by Equation 1.

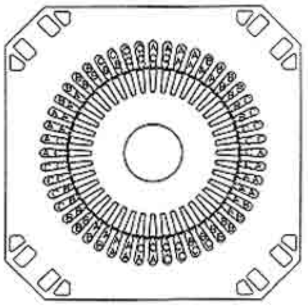


Figure 1: Typical AC Induction Motor Stator and Rotor Laminations

$N1 = 120 \times f / P$ (1)

$N1$ = rotational speed of stator magnetic field in RPM (synchronous speed)

f = frequency of the stator current flow in Hz

P = number of motor magnetic poles

For various numbers of motors poles, Table 1 shows the synchronous speeds based on 60 Hz and 50 Hz frequencies.

POLES	FREQ (Hz)	N1 (RPM)
2	60	3600
2	50	3000
4	60	1800
4	50	1500
6	60	1200
6	50	1000
8	60	900
8	50	750
10	60	720
10	50	600
12	60	600
12	50	500

AC Motor Synchronous Speeds, Table 1

The natural tendency is for the rotor to "follow" the rotating magnetic field and, at no-load, the rotor will turn at a speed y equal to Nl. Any difference in the rotational speed of the magnetic field and the rotor will result in a voltage being induced in the rotor squirrel cage winding. The resultant rotor current interacts with the magnetic field to produce torque. The difference in rotor mechanical speed versus magnetic field rotational speed is what is known as "slip".

The equivalent circuit for an AC induction motor can help visualize some of the motor characteristics. Figure 2a shows separate circuits for the stator and rotor, with the interaction between them modeled as a "transformer". This transformer has the unique characteristic of also changing the frequency of the signal! While the current in the stator is at the applied frequency of the motor power source, the rotor current flows at a frequency based on the slip of the motor.

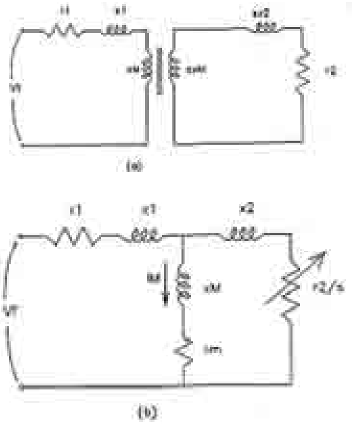


Figure 2: AC Induction Motor Equivalent Circuits

Rather than work with such a two part equivalent circuit having currents at different frequencies, the circuits of Figure 2a are typically modified to come up with a single circuit as shown in Figure 2b.

SPEED/TORQUE CURVES

As an AC induction motor is started, the values of resistance and reactance offered by the motor (or seen by the power source) will vary. At the instant of applying power to a stopped motor, the magnetic field is rotating much faster than the (stationary) rotor. This implies 100% slip, so r2/s is minimized. As a result, the current drawn at starting (locked rotor) conditions is quite high. Also, it is common to design rotor slots which have dramatically different impedance at high slip (say 60 Hz for starting) versus at typically less than I2 Hz slip (normal running). This changes the values of both x2 and r2 from starting to running conditions.

As a motor accelerates to speed from a standstill, the changing impedances result in a unique characteristic developed torque and current drawn during the time of acceleration. Depending on the design of the motor, a torque/current characteristic such as one of those shown in Figure 3 would typically result. The NEMA Design B motor is considered the most "general purpose" of these characteristic shapes, with Design C and D typically used for more "difficult to start" loads. Table 2 gives some ranges of characteristics for integral HP, 1200 and 1800 RPM motors.

4 & 6 POLE MOTORS 10 - 125 HP

PER UNIT DATA

NEMA DESIGN	LRA	LRT	BDT
A	N/A	1.0 - 1.65	2.0
B	5.3 - 5.9	1.0 - 1.65	2.0
C	5.3 - 5.9	2.0 - 2.5	1.9
D	5.3 - 5.9	2.75	N/A

Typical AC Induction Motor Speed/Torque/Current Data, Table 2

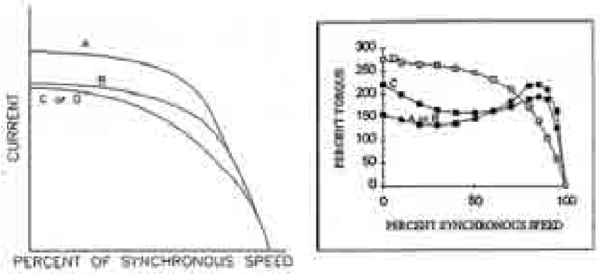


Figure 3: Typical AC Induction Motor Speed/Torque/Current Curves

As can be seen from all of these speed/torque curves, the current drawn by an AC motor in accelerating a load up to speed can be dramatically higher than the nominal running current. At the same time, the developed torque (during acceleration) may, in some cases, be less than the rated full load torque. Various methods exist to control the starting current drawn by an AC motor, but the torque per amp seen during starting is always much lower than at running conditions.

The nature of an AC induction motor acceleration to running speed is such that it can impose high stresses on the stator end turns and the rotor. The high current draw also stresses the upstream power system, including cabling, transformers, switchgear, etc. For this reason, there is often significant effort made to "control" AC motor starting and acceleration - both in terms of motor design as well as application.

EFFICIENCY AND LOSSES

Returning to the AC motor equivalent circuit of Figure 2b, we can identify three of the five basic component losses which exist in AC induction motors. The losses dissipated in the resistance of the stator and rotor windings, plus the core loss (eddy current and hysteresis losses in lamination steel) are modeled in the equivalent circuit. A fourth component loss is the friction and windage of the rotor, fan, bearings, etc. Finally, there is the "leftover' category of stray load losses. These are losses which are a compilation of various less easily modeled losses, but are often a significant loss in highly efficient machines. The stray load losses include eddy current losses in the conductors, core losses due to flux distortion with load, etc.

Since the friction and windage and core losses are essentially independent of load, while the other losses vary as the square of load (current), the efficiency of an AC induction motor falls off precipitously at light loads (see Figure 4).

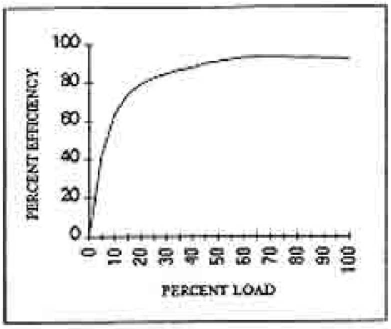


Figure 4: AC Induction Motor Efficiency vs. Load

ADJUSTABLE FREQUENCY, VARIABLE SPEED OPERATION

For steady-state (as opposed to starting) operation, AC induction motors offer a reasonably linear torque per amp and high power factor characteristic. This is seen in Figure 5 as the part of the speed torque curve between "breakdown RPM" and "synchronous (no load) RPM". It is this portion of the AC induction motor range of operation within which adjustable frequency drives function.

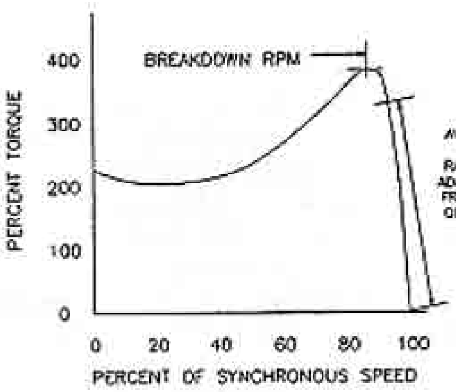


Figure 5: AC Induction Motor Speed Torque Curve

By varying both the frequency and voltage supplied to an AC motor, the controller can cause the motor to operate on a continuum of speed torque curves which allows operation in the "linear" region between breakdown and synchronous speeds (Figure 6). This then allows the motor to operate near its optimal torque per amp or maximum efficiency point for a given load and speed.

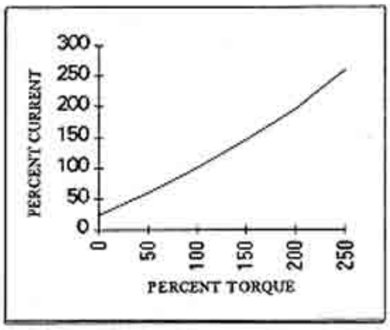


Figure 6: AC Induction Motor Steady State Operation

As long as the motor flux is maintained constant while the frequency and voltage are varied, the basic "shape" of the speed torque curve will remain unchanged. The motor flux is proportional to the internal "counter-emf" divided by the frequency of that generated voltage. This can be described as:

$$\Phi = k \text{ x } Eg / f \qquad (2)$$

where Φ is the motor flux,
and Eg is the internally generated voltage due to motor rotation,
and f is the stator frequency,
and k is a motor constant related to the winding turns, etc.

The motor counter-emf (Eg) can also be thought of as the voltage across the magnetizing reactance (xm) in the equivalent circuit of Figure 2b. Maintaining constant flux while the speed (frequency) is varied can then be seen as requiring constant ratio of Eg/f.

Since Eg is a motor internal voltage, this needs to be related to the terminal voltage of the motor. From the AC motor equivalent circuit, it can be seen that the voltage drops across the stator resistance and leakage reactance represent the "difference" between Eg and the terminal voltage Vt.

If a controller were to maintain a constant ratio of AL voltage to frequency (Vt/f), rather than Eg/f, this would result in a decreasing flux level at lower speeds (frequencies). The curves of Figure 7 demonstrate the effect of this failure to maintain the motor flux. It can be seen that the peak value of torque falls off at the reduced flux levels. In fact, the peak torque is approximately proportional to the square of the flux level, so the drop-off can be significant. The torque per amp is also proportional to the motor flux, so increased current draw for a given load will also result from reduced flux.

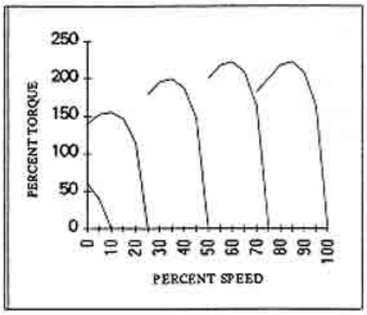


Figure 7: Speed Torque with Constant Terminal V/Hz

As a means to improve the system characteristics (beyond the curves of Figure 7), controllers often compensate for the difference between Vt and Eg in order to select tile correct voltage for a given frequency. This compensation is often referred to as "voltage boost". Since the major detrimental effect of constant Vt/f is at low voltages, low frequencies (low speeds), the voltage drop across the stator leakage reactance is usually ignored (as the impedance of an inductor is proportional to frequency). This leaves the drop across the stator resistance as the major source of a discrepancy between Vt and Eg at these low speeds.

Many controllers use a value of voltage boost which compensates for the IR drop of the stator at a current equal to the motor full load amps.

$$Vb = If1 \text{ x } r1 \quad (3)$$

Vb is the per phase (line-to-neutral) voltage boost,
rl is the per phase stator resistance,
Ifl is the motor full load current.

This would result in a voltage versus frequency characteristic as shown in Figure 8. A weakness in this technique of boosting voltage is that the value of Vb is only "correct" for a single value of load current. If the full load current is used to set the voltage boost, then the motor will be overfluxed for lighter loads, and underfluxed for overload conditions. Depending on the low speed performance required by a given application, this may or may not be a problem.

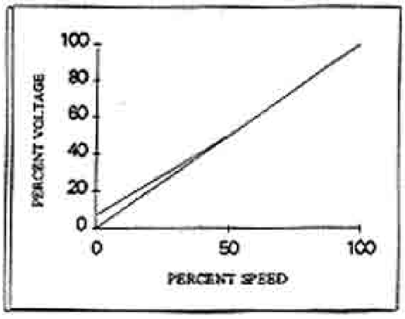


Figure 8: Low Speed Voltage Boost

"FIELD ORIENTED" CONTROL

In order to obtain better control of AC motor torque, adjustable frequency controls sometimes make use of a regulation scheme known as "field-oriented" or "vector" control. This technique is intended to control the motor flux, and thereby be able to decompose the AC motor current into "flux producing" and "torque producing" components. These current components can be treated separately (in the control), then recombined to create the actual motor phase currents. This results in a solution to the boost adjustment problem, plus provides much better control of the motor torque - which allows higher dynamic performance.

In order to accomplish field-oriented control, the controller needs to have an accurate model of the motor equivalent circuit. This model eliminates the need to set "volts-per-Hz" and "boost" as is done m scalar (non field-oriented) control schemes. The actual voltage seen at the motor is then a result of the motor equivalent circuit and the specific current being regulated by the controller.

One result of field-oriented control is that by virtue of the motor flux being maintained, the motor torque-per-amp can be held constant down to zero speed. An additional advantage results from the improved control (predictability) of motor output torque - that is, higher "dynamic" performance. This allows AC drives to serve applications requiring high "velocity loop bandwidth," such as servos.

CONSTANT POWER OPERATION

The discussions above regarding voltage boost and field oriented control as a means to maintain motor flux have been presented in regard to "constant torque" operation. This can also he thought of as operation "below base speed" (Figure 9).

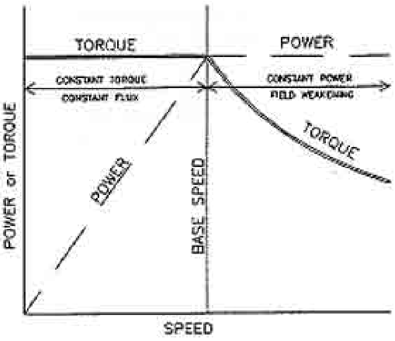


Figure 9: AC Motor Speed Ranges

Above the speed at which the output voltage of the controller is at maximum, the controller can no longer maintain constant flux as speed is increased further. This is equivalent to where a DC motor begins to be "field weakened" to achieve higher speeds. Both for AC as well as DC machines, voltage (armature voltage for DC) remains constant, so for constant load current, constant output power is available.

As the frequency supplied to an AC induction motor is increased (with voltage held constant), the "field weakening" causes a reduction in the motor peak torque capability as seen in Figure 10. This family of curves can alternatively be drawn as speed - power, rather than speed - torque curves (Figure 1). The fact that the peak power decreases as speed is increased by field weakening is the most "inherent" limitation to the "constant power speed range" of an AC drive.

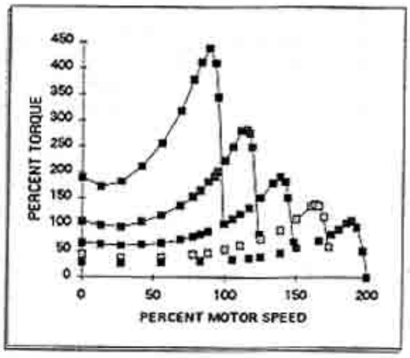


Figure 10: AC Motor Speed/Torque Curves Based on Field Weakening by Increasing Frequency with Constant Voltage

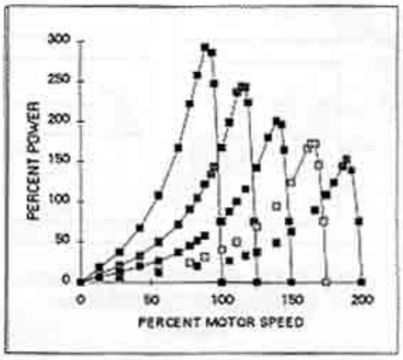


Figure 11: AC Motor Speed/Power Curves Based on Field Weakening by Increasing Frequency with Constant Voltage

NON-FUNDAMENTAL VOLTAGES CURRENT

Up to this point, we've talked about varying the voltage and frequency applied to an AC induction motor as if the voltages and currents were still sinusoidal in shape. In fact, depending on the type of adjustable frequency controller, various non-fundamental voltage and current components will exist (Figure 12).

The waveforms in Figure 12 are often looked at in the frequency domain (Laplace or Fourier transform). In the waveforms of Figure 12 a, b, c, d, the higher frequency components (non-fundamental components) are "harmonics' of the fundamental frequency. That is they occur at frequencies equal to integer multiples of the fundamental frequency. For the PWM waveforms of Figure 12 e, f, the switching (carrier) frequency is usually not synchronized to the fundamental frequency. This leads to a set of non-fundamental frequency components which are not true harmonics of the fundamental frequency.

Whether or not the non-fundamental current components are harmonics of the fundamental, they do not contribute to the normal production of torque. They can, in fact, produce pulsating (ripple) torques which lead to other problems. The non-fundamental voltages similarly do not provide fundamental flux for the development of torque.

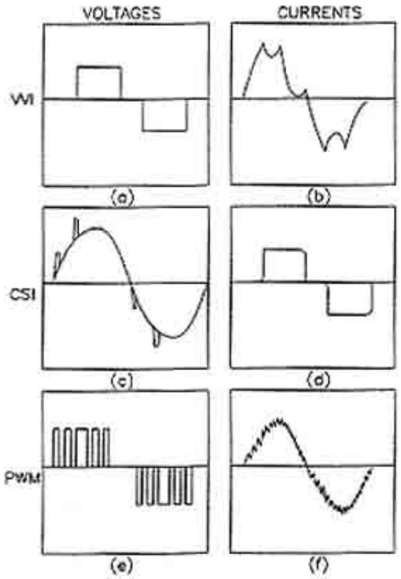


Figure 12: Typical Adjustable Frequency Controller Voltage and Current Waveforms

ADDITIONAL MOTOR LOSSES

While these non-fundamental components do not provide basic torque, they do cause motor losses. Since the stator winding carries the total current (fundamental and non-fundamental components), the RMS value of the total current produces the stator winding 12R loss. The RMS value of the non-fundamental currents can range from 1% of the fundamental to over 10%, depending on the controller and motor combination, as well as the operating point.

The non-fundamental components in the stator can also be “transferred” to the rotor by transformer action (induction). Depending on the specific motor design, including rotor slot details, the rotor may “see” a significant increase in its non-fundamental (non-slip frequency) current. This will then result in added rotor I2R losses.

The non-fundamental voltage harmonics will produce flux variations which are not adding to motor torque, but which do cause eddy current and hysteresis losses in the motor magnetic laminations. Again, the specific combination of controller and motor will strongly influence the magnitude of these additional losses.

HEAT DISSIPATION

Adding to the motor heating caused by the additional losses discussed above, a “self-ventilated’ (e.g. DPG, TEFC) motor WM have less ability to dissipate these losses at lower speeds (Figure 13).

For this reason, it is often appropriate to use a motor with ventilation which is speed-independent (TENV, DPFV, TEBC) when operating across a wide range of speeds. As can be discerned from Figure 13, the desirability of speed-independent cooling is typically more pronounced for larger machines.

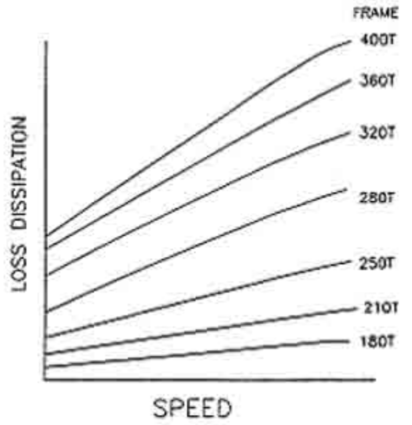


Figure 13: Influence of Speed on Heat Dissipation

In addition to the problem of loss of dissipation at lower speeds, the use of a TEFC or DPG motor for operation at high speeds can result in large windage losses, as well as acoustic noise problems.

SWITCHED VOLTAGE WAVEFRONTS

The use of semiconductor switching devices to create the adjustable frequency input to AC induction motors can result in some effects beyond the “non-fundamental components” issues. The waveforms seen in Figure 14 are expanded views of the PWM voltage of Figure 12 e. As power transistors have evolved, their ability to “turn on” quickly has also improved dramatically. This implies a high level of “dV/dt” as defined in Figure 14b. Both this high dV/dt as well as the higher peak voltages seen by a motor applied with this type of controller need to be considered in designing motors for these applications.

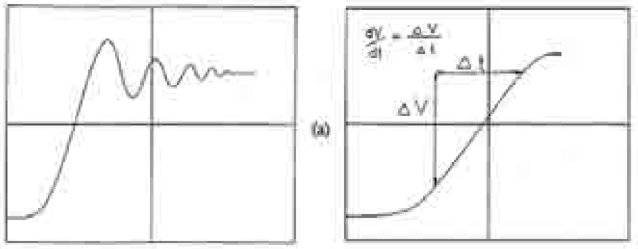


Figure 14: Adjustable Frequency Controller Output Voltage Waveforms

The higher peak voltages seen at the motor terminals provide a higher dielectric stress on the motor insulation system. These peaks occur at each transition (carrier frequency for a PWM controller) on each of the motor phases. Due to the repetitive nature of this voltage, an inadequate motor insulation system (from a dielectric standpoint) will often fall in a rather short period of time (days to months).

The high dV/dt of these switched wavefronts contributes to the overshoot and ringing of the voltage at the motor terminals, but also has an interesting effect of its own. Based on Equation 4, a high dV/dt can cause a high current flow in a capacitive circuit.

$$I = C \times dV/dt \qquad (4)$$

While motors are often not thought of as having a characteristic capacitance, there are both phase-to-ground as well as phase-to-phase capacitances associated with AC induction motors. This capacitive effect is “distributed’ in that the windings have various “Positions” relative to the stator core, as well as to the other phases. This causes the capacitively-coupled current flow to also be (unequally) distributed. These currents, while very short in duration, also occur at every transition (dV/dt) and can cause failure of an inadequately insulated motor in a short time.

Another result of these capacitively-coupled currents is that if a ground connection is not provided (from the motor frame), significant pseudo-square wave voltages will occur on the motor frame which can be a hazard to personnel. A proper ground connection will eliminate these voltages, but there will be fairly high frequency currents flowing to ground.

The leads connecting the controller to the motor also will experience some of the same capacitively coupled currents as the motor (phase to phase and phase to ground).

NOISE

Another effect of the non-fundamental waveforms of Figure 12 on AC induction motors is the possibility to produce acoustic noise. Beyond noise due to “windage” effects, the majority of motor noise is due to components deforming in a manner which can pump air in the audible frequency range.

While all structures have characteristic sets of natural frequencies and corresponding mode shapes, some of these are of more concern. If any of the non-fundamental waveform frequencies are closely aligned with motor natural frequencies, the forces produced by these voltages and currents may excite mode shapes which could result in high audible noise at a specific frequency.

The use of motor designs which have as “sparse” as possible a set of (potentially noise producing) natural frequencies is a good starting point to reduce opportunities for noise problems. By appropriate design of the electromagnetic structure, the force distribution of the higher frequencies can also be mitigated.

OVERSIZING/DERATING

An approach to applying AC induction motors to adjustable-h-frequency, variable-speed operation can be to oversize or derate motors for the application. This is an approach which may, in simple applications, be successful, but a number of potential hazards exist.

Whether or not a motor is derated/oversized will not be of any help if the insulation system is inadequate for the switched voltage wavefronts from the controller. A motor loaded to less dm full load can fail just as quickly as one fully utilized if the insulation dielectric capability is lacking.

A motor which is derated will have lower reactances, which, in a CSI application, may be fine, but can cause excessive current ripple in a PWM environment. This high ripple can cause IIET trips of the controller, overheating of the controller transistors, or motor overheating. Also, a derated motor will have low damping as a result of its low slip, which can cause instability problems in open-loop drives, or modeling problems in a field-oriented controller.

Since AC induction motors can have a significant level of no load (magnetizing) current compared to full load current, a derated motor will often operate at a reduced power factor at the application load. This can result in higher full load current which may exceed the continuous rated current of the controller.

CONCLUSIONS

AC induction motors are likely to continue to be reliable sources of fixed speed rotating power. Their successful use in variable speed applications is increasing. In order to avoid unsuccessful applications, the users, controller and motor manufacturers need to communicate well. This will allow appropriate matching of the load, motor, and controller.

AC DRIVES OFFER OPPORTUNITIES TO REDUCE MAINTENANCE COSTS

By Doug Weber, marketing manager, Allen-Bradley Drives Business, Rockwell Automation

Many users of AC drives are aware of the significant reduction in energy consumption that is offered when an AC drive is used to control the speed of a centrifugal fan or pump. Using a drive to operate these devices at, for example, 80 percent of their rated speed can cut energy costs in half. What is often overlooked is the far-reaching impact on the overall health of automated systems that AC drives can offer. In fact, converting a process from fixed speed to variable speed in itself can reduce wear and tear and reduce maintenance requirements for mechanical systems by reducing start/stop cycles and eliminating vanes, dampers, valves and other mechanical system components. In addition to these benefits, understanding the features offered by a variable speed drive can significantly reduce system maintenance and reduce overall operating costs.

MONITORING

Drives have somewhat limited monitoring capabilities compared to devices exclusively dedicated to preventative maintenance. By nature, however, they do monitor motor current and speed and can perform protective functions based on that information. Programmable Logic Controllers (PLCs) and other controllers, when connected to a drive via a communications network, can also monitor these values and provide warnings and reminders to maintenance personnel that something in the process has changed. For example, by monitoring the motor current and speed, it may become obvious that a motor is loaded more heavily than normal and that the mechanical system should be checked before a failure occurs.

MOTOR OVERLOAD

In more extreme situations, the drive itself will act to protect the motor. Almost all drives today have a built-in electronic motor thermal overload feature. When a motor is in a state of severe exertion, beyond its safe operating limits, the motor overload feature can reduce the output current or shut off the motor and protect it from thermal damage or catastrophic failure. Motor overload software uses an algorithm incorporating motor current, speed, and time as inputs to model the temperature of the motor. This may also be done with thermister feedback directly from devices buried in the motor windings, using actual temperature readings to determine motor stress. Multi-motor applications – those using one AC drive and more than one motor – will require the motor overload to be disabled since the drive would be unable to distinguish each individual motor's current to provide protection for individual motors. These applications require more advanced machine monitoring devices that can accept data from multiple sources to alert personnel of impending faults and failures.

S CURVE

S Curve and controllable acceleration and deceleration are other, often-overlooked drive features that help improve process performance and reduce maintenance. When a load transitions from steady state speed to accelerating or decelerating, the transition is usually instantaneous. The same is true when the transition is reversed. While not as dramatic, it is the industrial equivalent of "popping the clutch" on a stick-shift car. This jerking action puts considerable stress on mechanical components. In belt-driven systems, belts can fly off or break. In geared systems, the process can wear or break gear teeth.

AC drives can control this phenomenon through a feature called S Curve. Using the same analogy, it is the process equivalent of "feathering or slipping the clutch" to ease into acceleration or deceleration. S Curve controls the jerk, or rate of change of acceleration. It has long been recognized as an aid in the handling of very light conveyor loads, such as in a bottling line, but it can also play a significant role in extending the life of mechanical components. Lower mechanical stress means lower maintenance costs.

FLYING START

The Flying Start feature is used to reconnect the drive to a motor that is already spinning and, as quickly as possible, resume normal operation with minimal impact on load or speed. When a drive executes a normal start, it initially applies 0 Hz and ramps up to the commanded frequency. If the drive is started in this mode with the motor already spinning, large currents will be generated and an overcurrent trip may result if the current limiter does not react quickly enough. The likelihood of an overcurrent trip is further increased if there is a residual flux on the spinning motor when the drive starts. Even if the current limiter is fast enough to prevent an overcurrent trip, the end result is still to effectively decelerate the motor to a very slow speed and then reaccelerate it to the desired frequency. This can place extreme mechanical stress on the application, potentially causing costly downtime and repair costs while decreasing productivity.

In Flying Start mode, the drive's response to a start command will be to identify the motor's speed and begin its output synchronized in frequency, amplitude and phase to that of the spinning motor. The motor will then be reconnected at its existing speed and smoothly accelerated to the commanded frequency. This process eliminates overcurrent tripping and significantly reduces the time for the motor to reach its desired frequency. Since the motor is "picked up" smoothly at its rotating speed and ramped to the proper speed, little or no mechanical stress is present.

In some applications, such as large fans, wind or drafts may rotate the fan in the reverse direction when the drive is stopped. Flying Start will determine, not only the speed of the fan, but also its direction of rotation. It will then execute controlled deceleration to zero and reacceleration in the commanded in the system.

SKIP FREQUENCY

Some machinery may have a mechanical resonance points that must be avoided to minimize the risk of equipment damage. Let's use another automotive analogy. Many of us have experienced a severe "shimmy" in the steering wheel because the car's front end is out of alignment. Experience shows us that this shimmy can be severe at one speed, but speeding up or slowing down by just a few MPH will make the vibration stop. The car's misaligned front end has a mechanical resonance only at specific speeds. All rotating mechanical systems have these resonant points and many can be damaged if allowed to operate continuously at these speeds, causing system downtime and increased maintenance costs.

Drives offer a feature called skip frequencies or Critical Avoidance Frequencies to ensure that the motor will not continuously operate at one or more of these vibration points.

The frequency that causes the resonance is programmed into the skip frequency parameters, and a bandwidth is programmed around the frequencies to create a skip band that avoids the vibration-causing areas. Most drives offer multiple skip frequency parameters to accommodate different resonance points.

Normal acceleration and deceleration are not affected by the skip frequencies. The drive output will ramp through the band uninterrupted. When, however, a command is issued to operate continuously inside the established band, the drive will alter the output to remain outside the band until a new command is issued.

When mechanical resonant frequencies are identified and drives are programmed to avoid continuous operation at those frequencies, wear and stress from vibration is greatly reduced.

CURRENT LIMIT

An AC drive has control of the amount of current it supplies to a motor. Current limiting functions are often used to prevent mechanical damage. By limiting current or shutting down the operation, AC drives can reduce mechanical damage. In addition to current limiting to reduce torque, most Allen-Bradley drives have a feature called an electronic shear pin – a modern take on an old concept. Outboard boat motors, for example, are usually equipped with mechanical shear pins. If the propeller strikes the bottom of the lake, rather than break the prop, the shear pin breaks, mechanically disconnecting the propeller from the motor and saving the mechanical system (and the boat owner's pocketbook). Similarly, a drive's electronic shear pin feature can define a current limit level that would cause damage. If the torque in the motor ever exceeds the set limit, the drive will automatically shut off the motor.

By limiting torque to a set level, AC drives provide good protection for systems that can become jammed, such as chain conveyors. By not allowing a motor to power through the jam, chain breakage and other damage can be avoided.

TORQPROV

In addition to features that limit torque or set "shear pin" torque levels, the Allen-Bradley PowerFlex 700 AC drive has a TorqProv algorithm especially for applications that require coordination between a motor and a mechanical brake. Prior to releasing a mechanical brake, the drive checks the motor output phase continuity and verifies proper motor control (torque proving). The drive will also verify that the mechanical brake has control of the load prior to releasing drive control (brake proving). After the drive sets the brake, motor movement is monitored to ensure the brake's ability to hold the load. This functionality can be very useful in lifting applications because it reduces the risk of dropping a load or damaging mechanical equipment. In addition, coordinating the drive and brake action reduces wear on the mechanical brake because in normal operation, the motor is stopped before the brake is applied.

SPREADING THE WORD

Taking advantage of these drive features doesn't require a great deal of special training of plant personnel. Users need only be aware of the features and the benefits that the drives provide. By taking full advantage of the wide array of techniques already available, plant engineers can minimize the stress and abuse placed on valuable plant machinery, increase equipment uptime and reduce maintenance costs – key elements for boosting the bottom line. Plus, maintenance personnel will welcome the change as their jobs become less hectic with a little help from an unexpected place – the AC drive.

ADVANCES IN DRIVE TECHNOLOGY MEET TODAY'S DEMANDING APPLICATION REQUIREMENTS

Jon Simons, technology leader, Drives Business, Rockwell Automation

The last decade has witnessed remarkable transformation in variable frequency drive technology, including AC vector drive performance; expanded communications capabilities; smaller, more compact design; and integrated control capability driven by more powerful and faster microprocessors. Drive users can now optimize drive performance to meet a wide range of application requirements without the added cost of customization or complex programming. New technologies also give users the ability to satisfy their growing and varying needs, from standalone drives to complex, integrated systems.

VECTOR CONTROL DELIVERS RESULTS

Perhaps the biggest breakthrough over the past 10 years was the addition of vector control to AC drives. At the center of this technology is the use of a field-oriented control scheme that replaces a volts-per-hertz regulator core, found in most AC drives, with a high bandwidth current regulator that allows independent speed and torque control, while dynamically adapting to motor and load changes. The ability to identify flux and torque separately allows the drive to continuously regulate those same quantities in the motor, resulting in more precise and improved overall motor performance, including the ability to optimize efficiency.

Drive manufacturers continue to improve the performance capabilities of vector control AC drives, taking advantage of progress being made in microprocessor technology. Improved field-oriented control algorithms help optimize drive performance to meet the speed or torque requirements of the application. This enabled high-powered AC drives to outperform DC drives, including delivering torque independent of motor speed, with a quick reaction to shock loads. As a result, field-oriented control of AC drives combines the best advantages of DC drives – constant torque down to zero speed – with the best of the AC drives – simplified installation, tuning and maintenance.

In hoist and crane applications, tight demands on torque response require the drive to deliver high torque levels without losing control of the load and the ability to stop the load accurately and precisely. Likewise, applications such as mixers, centrifuges and extruders require a drive capable of delivering full torque immediately upon startup, constant torque throughout the operating speed range, and full torque down to zero speed. This helps ensure that an injection molding machine, for example, will generate proper material flow and produce high quality parts from the start, while minimizing scrap. For years, users relied on DC drives to meet these challenges, but users are now taking advantage of vector control AC drives that deliver a cost-effective, high-performance alternative.

INTEGRATED CONTROL CAPABILITIES

Other advances in drive technology center around logic control capabilities. These control features allow users to optimize general-purpose drives for specific applications without having to order a special drive or write additional code in a separate processor.

Because the embedded control is tightly coupled, users achieve higher speed and throughput. For example, users may be able to position-synchronize a printing press to boost throughput, or more quickly and precisely move items within a work cell, such as lifting and moving vehicle parts on an automotive assembly line.

By embedding the logic right into the drive, users also can reduce the size of the drive-control package, and improve reliability by minimizing the number of required connections. While applications with large I/O requirements may still require a separate controller, many simple processes can benefit from the improved speed and efficiency of a standalone drive unit.

DRIVES AND POSITIONING APPLICATIONS

Another significant advance in AC drive technology is its use in applications that require precise positioning during production. In the past, AC drives weren't designed to place products and materials with the accuracy required to be effective. Although high performance drives can sometimes match the accuracy of servo motion technology, more commonly, today's drives are replacing older mechanical systems, such as those on assembly lines.

For example, the Ford Motor Company's St. Paul, Minn., plant recently replaced hydraulic and mechanical transfer systems on the assembly line producing Ford Ranger plants with Allen-Bradley PowerFlex 700S drives from Rockwell Automation. The drives contain an embedded controller, DriveLogix, that enables the drive to meet the exact positioning requirements of the assembly line. Using the PowerFlex 700S and Point-to-Point Positioning Application software, the drives direct the truck frames to exactly the point needed on the assembly line, streamlining production and reducing maintenance associated with complex mechanical systems.

EASE OF USE TAKES PROMINENCE

As microprocessors continue to get faster, more powerful and less expensive, drive manufacturers will continue to look for ways to reduce the size, cost and complexity of AC drives, while enhancing performance. On the performance side, new techniques allow higher bandwidths of control even when faced with machine resonances. Still, while some end users demand more application versatility and flexibility, others need ease-of-use features, rather than technological advances.

One of the biggest areas of technology innovation is occurring in the area of drive programming and configuration, where simplification and ease of use is driving the developments. The use of programming wizards for drive startups is fast becoming a key area of focus. These tools operate much like the setup programs in new PCs, where after a few prompts, the wizard automatically installs the software and required drivers, sets all the parameters and recognizes the hardware devices that are plugged into the PC.

For example, new drive programming wizards will prompt the user for information about the application, size of the motor, and other critical information. It will then automatically set up all the parameters to meet the defined application and hardware requirements.

For more complex installation, like a centrifuge or lifting processes, the wizard might request some additional parameters, such as the type of application, the speed of the process, and the weight of the load. It will then automatically adjust the parameters to optimize the drive for that application. These tools can dramatically reduce drive startup and commissioning time and improve setup accuracy by eliminating a significant amount of manual configuration.

One consequence of increased connectivity is that individual devices will no longer be viewed and managed as isolated components, but rather as part of an integrated system. That's because users will be able to program, control and troubleshoot drives, controllers, relays, I/O and motion devices from a common interface using a single software package. This includes the ability to add logic using common software tools with the same look and feel — no matter whether the application involves a small drive in a standalone process, or a high-performance drive as part of a large PLC-based, integrated and networked system.

In addition to reduced setup and operational costs, a key benefit of this integrated environment is that users will be able to easily save all of their drive parameters and control logic in a single database. In the event of a failure, replacement and restoration of the original drive parameters would be a relatively simple process.

The proliferation of high-speed Ethernet and wireless networks on the plant floor enables users to continually increase the ability to monitor and control drives and share information. New technologies such as time synchronized services in Ethernet will provide even higher levels of control. The drive can then become an "information window" to the production process.

Improved diagnostics is another feature applied to newer drives as maintenance practices continue to be more proactive. For example, with current technology, users typically have a small window of time (a few minutes) until the drive will trip as a result of an overload condition. Enhanced thermal regulators extend this time by optimizing the IGBT switching patterns during periods of thermal stress. The new diagnostic tools will allow users to perform a trend analysis over longer periods of time to show that a drive may be drawing more current than normal to achieve the same speed.

With access to more detailed information over longer periods of time, users will be able to potentially predict problems and prevent catastrophic failures. Moreover, the improved quality and availability of data will enable maintenance personnel to be better positioned to troubleshoot, helping to reduce costs and improve uptime. Simple descriptions are given to pinpoint problems, not obscure fault codes.

CONCLUSION

Advances in AC drive technology are helping manufacturers increase productivity and save energy throughout their facilities. Increases in technology that delivers more precise speed and torque, as well as enhanced communications capabilities, reduce downtime and increase throughput, as well as give a more accurate picture of the manufacturing environment.

Also, as drives manufacturers continue to pack more performance in smaller packages, end users will have greater flexibility in selecting the right drive to meet future application needs. And with simplified setup tools, improved diagnostics and increased networking capabilities, users will have greater opportunities to maximize the return on their drive technology investments.

FAULT ZONE ANALYSIS/SIX PART SERIES ON IDENTIFING MOTOR DEFECTS

Noah P. Bethel, PdMA Corporation

Electrical maintenance personnel have for years been limited to troubleshooting with no more than a multimeter and a megohmeter. This, unfortunately, does not provide enough information to allow most technicians to feel totally confident in determining if an electrical problem exists or not. A mechanical operator once said, "If a problem exists with a piece of equipment, and there is an electric cable within fifteen feet of it, then it must be an electrical problem!" If you are involved with electric maintenance, you have probably heard at some time in your career, "It must be the motor." If you are into mechanical maintenance you have likely heard, "It's probably the pump. Let's uncouple it."

This has been an on-going battle and, up to recently, technology has been primarily developed for the mechanical side. Vibration shows a two times line frequency (2FL) spike and that must mean it's electrical. Right?... Wrong!!!! There are so many variables producing a 2FL today that removing a motor from service for an electrical repair due only to a high 2FL is a mistake, possibly an expensive one. The best thing you could hope for is that the repair facility will call back asking, "What do you want done to this perfectly good motor?" More recently, the battleground has moved from the motor vs. pump to the motor vs. drive. It seems, as soon as technology is developed to solve a debate, that another debate appears, advancing technology even further.

"Resistance to ground testing is all we need." I find this statement hard to believe. How many times have we been nervous restarting a tripped motor after verifying with our trusty megohmeter that, "The motor is fine". The fact is numerous reasons can exist which cause a motor to trip that will not be seen by a megger, such as a turn-to-turn short. Breakdown in the insulation between individual turns of a winding can occur inside a stator slot or at the end turn and be completely isolated from ground. Phase-to-phase shorts can occur the same way. If these faults are left unattended, they can result in rapid deterioration of the winding, potentially ending in a complete motor replacement. Restarting of a motor that has tripped should be considered only after these faults have been factored out.

Troubleshooting an electric motor that is suspected to have an electrical problem should not result in the statement, "The motor is fine". Although someone with years of experience and tons of credibility may be able to get away with such a simple statement, most technicians won't find the same positive response from their supervisor, engineer, or plant manager. To confidently report the electrical condition of a motor and ensure that your recommendation is taken seriously, there are six areas of interest known as Fault Zones that must be looked at during the troubleshooting effort. Missing any of these zones could result in missing the problem and losing credibility in your troubleshooting skills.

POWER QUALITY

Power Quality has recently been thrust in the limelight by high demand on the utilities and the popularity of AC and DC drives. With high demand, the concern for power factor penalties and demand charges has increased. The variable frequency drives (VFD's) and other non-linear loads can significantly increase the distortion levels of voltage and current. How can this distortion be minimized? What equipment is required, and is the concern purely financial or is equipment at risk?

In Part 1 of this six part series we will discuss the real meaning of power quality problems as it pertains to motor health. We'll discuss voltage and current harmonic distortion, voltage spikes, voltage unbalance, power factor, and the basic principle that ties them all together…HEAT.

POWER CIRCUIT

The power circuit refers to all the conductors and connections that exist from the point at which the testing starts through to the connections at the motor. This can include circuit breakers, fuses, contactors, overloads, disconnects, and lug connections. A 1994 demonstration project on industrial power distribution systems found that connectors and conductors were the source of 46% of the faults reducing motor efficiency. In Part 2 of this six-part series we will discuss the impact of power circuit problems on motor health.

INSULATION CONDITION

This refers to the insulation between the windings and ground. High temperatures, age, moisture, and dirt contamination all lead to shortened insulation life. It has been said that if plants would just use the space heaters available to keep the insulation dry, then doubling the life of our motors would not be out of the question. In part 3 of this six-part series we will discuss the standards governing insulation condition and how best to apply them to ensure the ground insulation on our motors has the longest possible lifespan.

STATOR CONDITION

When we mention the stator, we are referencing the DC or 3 phase AC windings, insulation between the turns of the winding, solder joints between the coils, and the stator core or laminations. This fault zone creates a lot of debate as to the cause and rate of failure. In Part 4 of this six part series we will discuss the various root causes of stator faults and how to identify conditions conducive to stator faults so they can be corrected.

ROTOR CONDITION

This refers to the rotor bars, the rotor laminations, and the end rings of the rotor. In the 1980s, a joint effort between EPRI and General Electric showed that 10% of motor failures were due to the rotor. The rotor, although a small percentage of the motor problems, can influence other fault zones to fail. In Part 5 of this six part series we will discuss the various fault mechanisms of rotor failures, the impact on motor health and the severity of rotor faults based on rotor design.

AIR GAP

This relationship references the air gap between the rotor and stator. If this air gap is not evenly distributed around the 360 degrees of the motor, uneven magnetic fields can be produced. These magnetic imbalances can cause movement of the stator windings, resulting in winding failure, and electrically induced vibration, resulting in bearing failure. In Part 6 of this six part series we will discuss the various types of eccentricity, what may cause them and how to identify air gap anomalies using static and dynamic test methods.

CONCLUSION

In conclusion, the term “The motor is fine” is just not enough to ensure that we are taken seriously and that a true assessment of the motor health has been performed. If the decision is up to you as to what to do in a troubleshooting or diagnostic situation, look at the whole picture. If at all possible, do not make a quick decision. Break the system down into its individual fault zones, test each fault zone completely with every technology available to you, and finally make your recommendations written or verbal using the terminology used in fault zone analysis to express your confidence and capabilities.

PART 1: POWER QUALITY

By developing a methodical step-by-step process, the EMAX Power Analysis test results can quickly be used to assess three of the six Fault Zones. These Fault Zones are derived from the most common electrically related motor failures in an industrial environment. This article focuses primarily on the Power Quality Fault Zone, followed by a recommended process to evaluate the data recorded during a Power Analysis (PA) capture.

Power Quality refers to the condition of the voltage and current signal. Mechanisms that can cause poor power quality include single and three phase non-linear loads, variable frequency drive units, starting and stopping of nearby equipment, voltage spikes, and more. These influences can cause excessive harmonics on the distribution system, which can result in overheating of the insulation system.

POWER QUALITY = VOLTAGE QUALITY

The common term is Power Quality, but what we are actually evaluating is the quality of the voltage that is being supplied to the motor circuit. The power supply system can only control the quality of the voltage; it has no control over the currents that a particular load might draw.

PdMA’s EMAX Power Analysis test allows a technician to take a Power Quality snapshot in order to see the condition of the voltage signal and evaluate the effect it will have on the motor. The actual sample time for the simultaneous measurement of the three voltage and current phases takes 0.17 seconds. From this snapshot, the technician focuses primarily on the three phase-to-phase voltages that power the motor and determines what effect they are having on motor performance.

Data used to evaluate Power Quality is located in the phase-to-phase voltage section of the Results Page (Figure 1). Fundamental RMS, Total RMS, Crest Factor (CF), and Total Harmonic Distortion (THD) are listed for each of the phase-to-phase voltages. The average voltage and percent imbalance are also listed. Additionally, recommended NEMA derating factors are provided for both phase-to-phase voltage imbalance and Harmonic Voltage Factor (HVF).

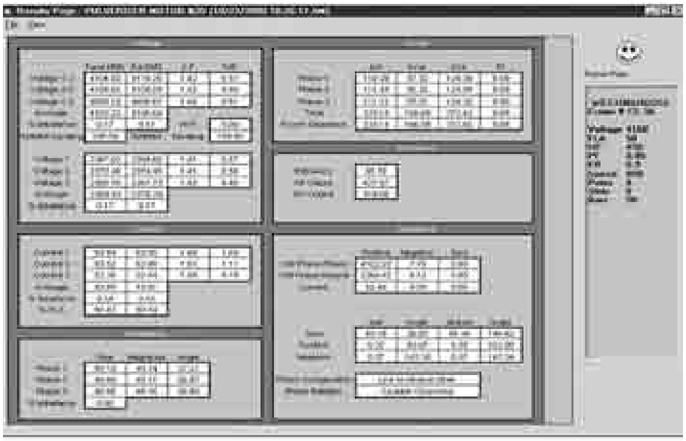


Figure 1

PHASE-TO-PHASE VOLTAGE IMBALANCE

When line voltages applied to an induction motor are not equal, negative sequence currents are introduced into the motor windings. These negative sequence currents produce an air gap flux rotating opposite the rotation of the motor. This reduces motor torque, affecting its operation and increasing the temperature rise of the motor.

NEMA provides a recommended derating factor based on percent voltage imbalance (Figure 2). Do not run a motor when the voltage imbalance is greater than five percent (per NEMA MG-1). With a phase-to-phase voltage imbalance, rated horsepower of an induction motor should be multiplied by the derating factor. If the load on the motor exceeds this derated value, take steps to correct the imbalance. Running the motor with the imbalanced voltage will cause excessive temperature rise in the windings and damage the insulation.

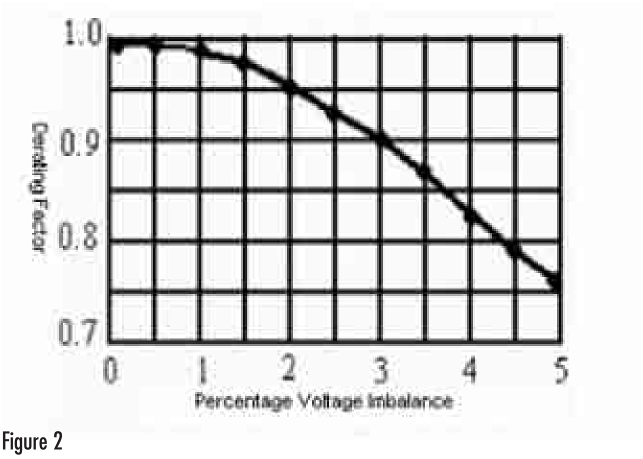


Figure 2

TERMINAL VOLTAGE

Terminal voltage has a major effect on motor performance. The effect of low voltage on electric motors is well known and understood; however, the effect of high voltage on motors is often misunderstood. In the next paragraphs we cover the effects of low and high terminal voltages.

LOW VOLTAGE

When a motor is operated below nameplate rated voltage, some of the motor's characteristics will change slightly and other characteristics more dramatically. To drive a fixed mechanical load, a motor must draw a fixed amount of power from the circuit. The amount of power is roughly related to the voltage times current. So with a lower voltage, there will be a rise in current to maintain the required power. This in itself is not alarming, unless the rise in current exceeds the nameplate current rating for the motor. When this happens the buildup of heat within the motor will damage the insulation system.

Aside from the possibility of over-temperature and shortened insulation life, other important effects on the motor's performance need to be understood. Starting, pull-up, and pull-out torque of induction motors all change based on the applied voltage squared. Thus, a 10% reduction from nameplate voltage (100% to 90%, 480 to 432 volts) would reduce the starting, pull-up, and pull-out torque by a factor of .9 X .9. The resulting values would be 81% of the full voltage values. At 80% voltage, the result would be 64% of the full voltage values. Clearly, it would be difficult to start those hard-to-start loads under such conditions. Similarly, the motor's pull-out torque will be much lower than during normal voltage conditions.

HIGH VOLTAGE

A common misconception is that high voltage tends to reduce current draw on a motor, since low voltage increases current. This is not always the case. High voltage on a motor tends to push the magnetic portion of the motor into saturation. This causes the motor to draw excessive current in an effort to magnetize the iron beyond the point to which it can easily be magnetized. Generally, motors will tolerate a certain change above nameplate voltage; however, extremes above this value will cause the amperage to go up with a corresponding increase in heating and a shortening of motor life. For example, older motors were rated at 220/440 and had a tolerance band of +/-10%. Thus, the voltage range for the 440-volt motor would be 396 to 484. Even though this is the so-called tolerance band, the best performance would be at rated voltage. Operation at the ends of this band would put unnecessary stress on the motor.

These tolerance bands are in existence not to set a standard that can be used all the time, but rather to set a range that can be used to accommodate the normal hour-to-hour swings in plant voltage. Continuous operation at either the low or high end of the band will shorten the life of the motor.

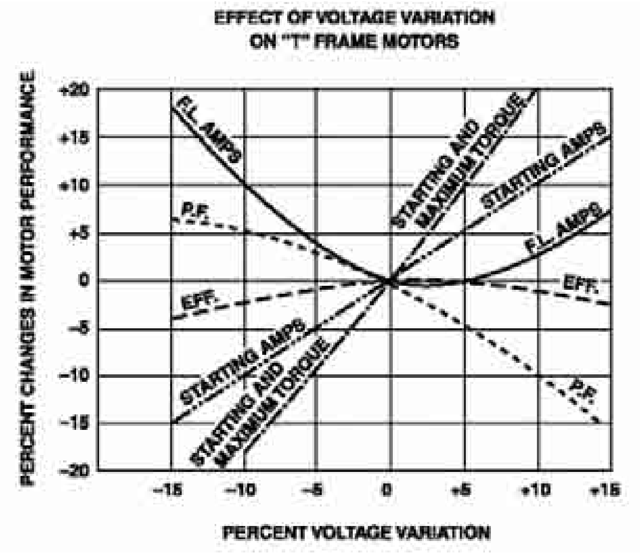


Figure 3

The graph shown in Figure 3 is widely used to illustrate the general effects of high and low voltage on the performance of T frame motors. It is okay to show general effects, but remember, these effects will change slightly from one motor design to another.

In older plants, some compromises may have to be made because of the differences in the standards for old motors (220/440) and the newer T frame standards (230/460), but a voltage in the middle of these ranges will generally result in the best overall performance. High voltages will always tend to reduce power factor and increase losses in the system, which results in higher operating cost for the equipment and the system.

The following guidelines are provided for assistance in evaluating the voltage of a motor circuit:

- Small motors tend to be more sensitive to over-voltage and saturation than large motors.
- U-frame motors are less sensitive to over-voltage than T frames.
- Premium/High efficiency motors are less sensitive to over-voltage than standard efficiency motors.
- Over-voltage can drive up amperage and temperature even on lightly loaded motors; thus, motor life can be shortened by high voltage.
- Full load efficiency drops with either high or low voltage.
- Power factor improves with lower voltage and drops sharply with high voltage.
- In-Rush current goes up with higher voltage.

Simply put, the best life and efficient operation of electric motors occurs when motors are operated at voltage as close to nameplate ratings as possible.

HARMONICS

NEMA DERATING FOR HARMONIC CONTENT, HARMONIC VOLTAGE FACTOR (HVF)

The presence of harmonic distortion in the applied voltage to a motor will both increase electrical losses and decrease efficiency. These losses will increase motor temperature, resulting in even further losses. To aid the technician in evaluating the effect that the harmonic content of the voltage is having on the motor's performance, EMAX provides the HVF and recommended derating factor.

Harmonics is the name given to distorting signals that are sinusoidal in shape and occur in multiples of the fundamental frequency. Non-linear loads generate these harmonics.

Linear loads are electrical load devices that, in steady state operation, present essentially constant impedance to the power source throughout the cycle of applied voltage. An example of a linear load is an induction motor. Note how the current is proportional to the voltage throughout the sinewave (Figure 4).

Non-linear loads are electrical loads which draw current discontinuously or whose impedance varies throughout the cycle of the input AC voltage sinewave. Examples of non-linear loads in an industrial distribution system are arc lighting, converter power supplies for VFDs (6 and 12 pulse), and DC power supplies. An example of a discontinuous current draw is shown in Figure 5, a phase of voltage and current supplying a VFD.

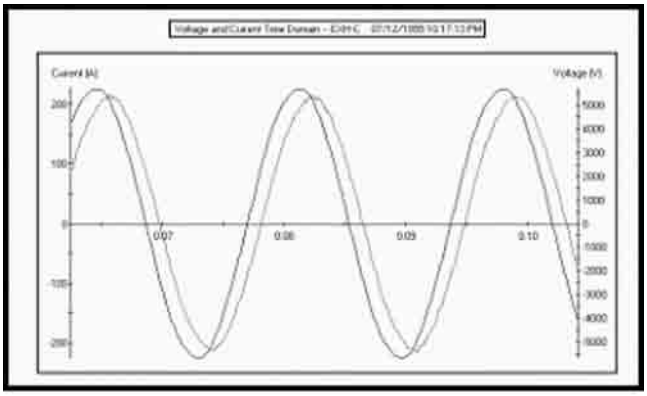


Figure 4

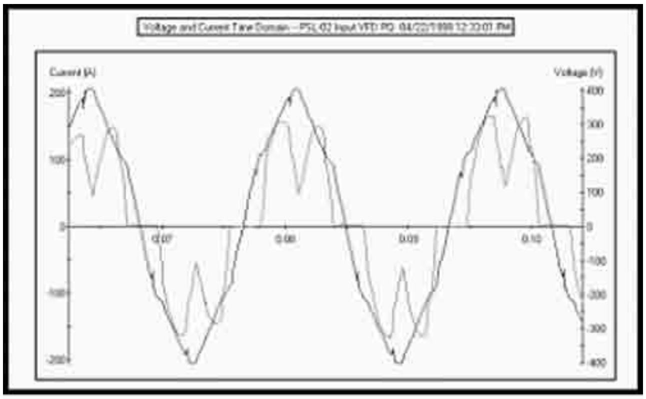


Figure 5

High harmonics can result in a temperature rise in motor temperature. NEMA has addressed this temperature rise during operation and whether the motor needs to be derated due to harmonic distortion of the voltage signal. In NEMA's Standards Publication Number MG 1, the Harmonic Voltage Factor (HVF) derating curve is provided to aid the technician in evaluating the severity of the problem.

When performing PA testing of motor circuits, the EMAX samples the applied voltage signal. It analyzes the voltage waveform, identifies the fundamental frequency and all harmonics present and their percent of the waveform. With this information the HVF is calculated and, if required, recommended derating per NEMA guidelines is provided. The HVF Derating Curve is shown in Figure 6.

NOTE: The curve does not apply when the motor is operated at other than rated frequency or when operated from a variable voltage or frequency source (VFD).

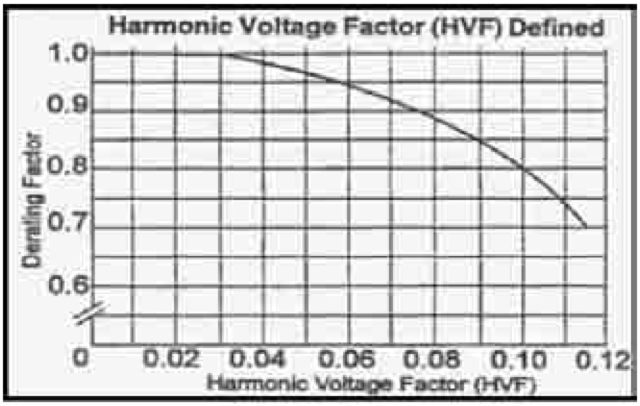


Figure 6

There is usually no need to derate motors if the voltage distortion remains within Institute of Electrical and Electronic Engineers (IEEE) Standard 519-1992 limits of 5% Total Harmonic Distortion (THD) and 3% for any individual harmonic. Excessive heating problems begin when the voltage distortion reaches 8 to 10% and higher. Such distortion should be corrected for long motor life.

CONCLUSION

The MCEMAX Power Analysis test provides a wealth of detailed information for identifying the power quality in your distribution system. In addition, this simple-to-perform test also provides the data required for detailed evaluation of motor circuits that utilize variable frequency drives. Phase-to-phase voltage, harmonic distortion, bus voltage, and total harmonic distortion all have an effect on the performance and condition of a motor. The MCEMAX tests provide you with what you need to know to make the informed decisions that lead to a successful motor management plan.

PART 2: POWER CIRCUIT

When evaluating the condition of any Fault Zone, it is a good practice to use as many technologies as possible. The focus of this article is to describe the Power Circuit and how to develop methodologies to identify anomalies within the Power Circuit.

Power Circuit refers to all the conductors and connections that exist from the power supply bus to the connections at the motor. This can include circuit breakers, fuses, contactors, overloads, disconnects, and lug connections. A 1994 study on industrial power distribution systems found that connectors and conductors were the source of 46% of the faults reducing motor efficiency. Many times a motor, although initially in perfect health, is installed into a faulty power circuit. This causes problems like voltage imbalances, current imbalances, etc. As these problems become more severe, providing the same horsepower output from the motor requires more current, causing temperatures to increase and insulation damage to occur.

One test provided by the MCEMAX to assist in analyzing the power circuit is the Power Analysis test. The Power Analysis test is performed on energized AC Induction, AC Synchronous, AC Wound Rotor Motors, and motors being powered by a VFD. The Power Analysis test indicates anomalies in the power circuit, power quality, and the stator fault zones. The focus of this article is the power circuit fault zone.

High resistance connections in the power circuit result in unbalanced terminal voltages at the motor. The consequences of the unbalanced terminal voltage are: overheating of the components adjacent to the high resistance connection, loss of torque, other phases drawing additional current to compensate, overheating of the insulation system, and a decrease in motor efficiency. Voltage imbalances will cause the motor to draw more current in order to perform the required work. Therefore, not only does the customer face premature motor burn out (or single-phase), but also they may potentially pay for extra kilowatt-hours and possibly a demand penalty.

Another result of voltage imbalance is the creation of negative sequence currents. These currents are named negative sequence because of the development of a magnetic field opposing motor rotation. This added load requires the motor to draw more current to power the load being driven. The long-term effect will be shortened insulation life due to the added thermal stress.

The values from the Power Analysis test that are used to evaluate the health of the power circuit are: phase-to-phase voltage, phase-to-phase current, and their respective imbalances. These measured values are recorded and compared against industry standards. Due to the negative effects from an imbalanced bus voltage, NEMA MG-1 recommends that a motor not operate if the voltage imbalance reaches 5%. NEMA provides a Derating Curve that shows a factor for derating motor horsepower due to the voltage imbalance experienced by the motor.

An unbalanced power delivery not only causes a voltage imbalance, but it will also cause a much higher percent current imbalance. Some thumb rules to apply when troubleshooting the power circuit.

- A 1% voltage imbalance can result in a 6–7% current imbalance, according to the Electrical Apparatus Service Association (EASA).
- A 3.5% voltage imbalance can raise winding temperatures by 25%, according to the Electrical Power Research Institute (EPRI).
- A 10 Celsius increase in winding temperature (above design) can result in a 50% reduction of motor life.

Phase voltage unbalance causes three-phase motors to run at temperatures greater than their published ratings. This excessive heating is due mainly to negative-sequence currents attempting to cause the motor to turn in a direction opposite to its normal rotation. These higher temperatures soon result in degradation of the motor insulation and shortened motor life. The percent increase in temperature of the highest current winding is approximately two times the square of the voltage unbalance. For example, a 3% voltage unbalance will cause a temperature rise of about 18%. 32 x 2 = 64

The greater the unbalance, the higher the motor winding temperature and the sooner the insulation will fail. NEMA standards recommend a maximum voltage unbalance of 1% without derating the motor. The motor can be derated down to 75% for a maximum of a 5% voltage unbalance. If the voltage unbalance exceeds 5%, it is recommended that the motor not be operated.

Now that the negative effects from unbalanced voltage and current due to power circuit anomalies have been discussed, how does the MCEMAX tester identify these anomalies? The easiest method to test a power circuit is using the Power Analysis test while the motor is under normal operating condition.

A current imbalance is a possible indication of a high resistance connection. However, a voltage as well as a current imbalance is a better indicator. What determines whether both imbalances are present in the event of a high resistance connection is the test location.

Voltage and current imbalances aren't both a requirement in the event of a fault in the power circuit. There can be many different looks to a high resistance connection, a power circuit component failure, or an imbalance that points to another fault zone.

Trending power circuit anomalies is most effective at similar loads. Higher loads may result in the fault being more obvious due to the stresses being greater at higher loads. The easiest way to verify the current draw of a motor is by looking at the % FLA in the Current section on the Results page (Figure 7).

Figure 7

Here, the technician's awareness to properly troubleshoot the power circuit will prove invaluable. As mentioned earlier, a current imbalance is a possible indicator of a power circuit anomaly. This is because the location of the anomaly in reference to the EMAX voltage test leads will show different imbalances. However, measured current values are consistent regardless of test location. Figure 8 shows how voltage readings can change based on test location.

If the test is being performed upstream of the anomaly, then there will only be a current imbalance, and if the test is downstream, there will be both a current and voltage imbalance. If the technician can't safely get closer to the motor for retesting, then further troubleshooting, by using the MCE Standard Test, should be performed when the motor is de-energized.

Loads using three-phase power sources are subject to loss

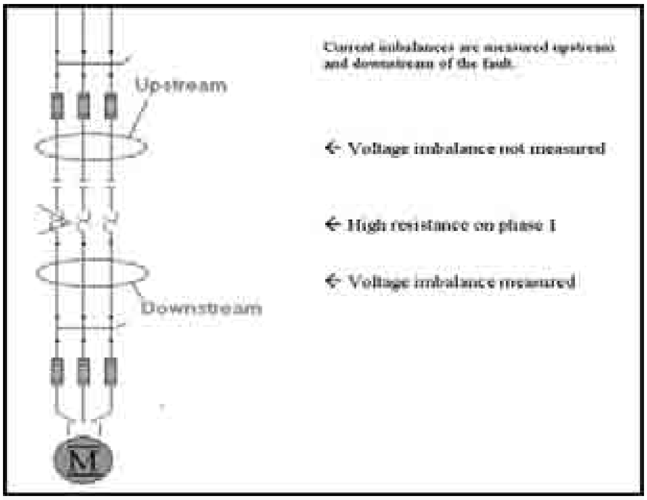

Current imbalances are measured upstream and downstream of the fault.
Upstream
← Voltage imbalance not measured
← High resistance on phase 1
← Voltage imbalance measured
Downstream
M

Figure 8

of one of the three phases from the power distribution system. This condition is known as single-phasing. The loss of one phase, or leg, of a three-phase line causes serious problems for induction motors. The motor windings overheat due primarily to the flow of negative-sequence current, a condition that exists anytime there is a phase voltage imbalance. The loss of a phase also inhibits the motor's ability to operate at its rated horsepower.

CONCLUSION

In conclusion, a high resistance connection results in voltage and current imbalances, which reduces the horsepower rating significantly. When a good motor is installed into a faulty power circuit, it causes problems with power imbalances, as well as, negative sequence currents. As the problems become more severe, the horsepower rating of the motor drops causing temperatures to increase resulting in overheating of adjacent components, damage to the rotor, stator, insulation, shortened motor life, reduced motor efficiency, motor failure, or fire. While damage to the rotor, stator, or insulation might be symptoms of a problem; the root cause still lies with the power circuit. Replacing the motor without fixing the high-resistance connection causes the failure cycle to begin again.

PART 3: INSULATION

The importance of sound electrical insulation systems has been acknowledged from the early days of electricity. As the years passed and the electrical industry expanded, the need for improved electrical insulation system testing became even more significant. The designs and applications of electrical equipment are almost infinite in their variety, but all units have one common characteristic. For electrical equipment to operate properly, one of the most important characteristics is that the flow of electricity takes place along well-defined paths or circuits. These paths are normally limited to conductors, either internal or external to the electrical component. It is important that the flow of current be confined; not leaking from one path to another through material not intended to be a conducting path.

Deterioration of insulation systems can result in an unsafe situation for personnel exposed to the leakage current. Ensuring that the insulation system is confining the flow of electrical current to the intended conducting path insures that personnel coming into contact with the insulation are not at risk of becoming a lower resistance conductor path for current-to-ground than the intended path.

Just as the walls of a pipe contain the flow of fluid, the insulation surrounding a conductor confines the flow of electric current. The walls of a pipe may have impurities, cracks, or other defects that limit its ability to withstand the pressure of the fluid. The insulation may develop impurities, cracks, or other defects that limit its ability to withstand electrical potential, which is the force or voltage that drives the flow of electrons, we call current, through the electrical circuit.

Despite great strides in electrical equipment design in recent years, the weak link in the chain is still the insulation system. When electrical equipment fails, more often than not the fault can be traced to defective insulation. Even though an electric motor is properly designed and tested prior to installation, there can be no guarantee that a fault in the insulation will not occur at some time in the future.

Many outside influences affect the life of electrical insulation systems. Outside influences include contamination of the insulation surfaces with chemicals from the surrounding atmosphere that attack and destroy the molecular structure, physical damage due to improper handling or accidental shock, vibration, and excessive heat from nearby industrial processes. Voltage transients in the conductors inside the insulation, such as surges or spikes caused by variable frequency drives, can lower the dielectric strength to the point of failure. The deterioration occurs in many ways and in many places at the same time. For example, as chemicals and/or heat change the molecular structure of the insulating materials, they become conductive, allowing more current to be forced through them by voltage resulting in leakage current.

Properly conducted insulation system testing, analysis of the data collected, and appropriate corrective action can minimize the possibility of failures. Therefore, the significance of understanding insulation system testing has never been more important.

SAFETY

IEEE 43-2000 claims that before any insulation testing can take place, safety must be addressed. It is not safe to begin testing until the discharge current is negligible and the there is no discernable return voltage. The return voltage should be less than 20V after the ground is removed. The MCE (Motor Circuit Evaluation) tester checks for this voltage before allowing testing. In order to start testing, there needs to be less than 15V line-to-neutral voltage before the test will begin (Figure 9).

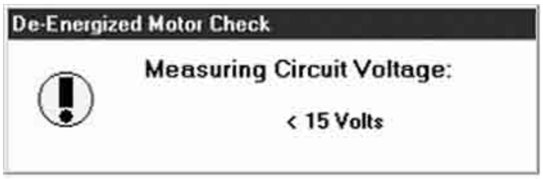
Also for testing at 5000V, the lead between the tester and the winding must be appropriately insulated and spaced from ground, otherwise, surface leakage currents and corona loss may introduce errors in the test data.

DEFINITIONS

By definition, the insulation resistance is made up of the applied direct voltage across the insulation divided by the total resultant current. The total current is the sum of four different currents: surface leakage, geometric capacitance, conductance, and absorption.

The surface leakage current is constant over time. Moisture or some other type of partially conductive contamination present in the machine causes a high surface leakage current, i.e., low insulation resistance.

The geometric capacitance current is a reversible compo-


De-Energized Motor Check

Measuring Circuit Voltage:

< 15 Volts

Figure 9

nent of the measured current on charge or discharge that is due to the geometric capacitance. That is the capacitance as measured with alternating current of power or higher frequencies. With direct voltage this current has a very short time constant and does not affect the usual measurement.

The conduction current in well-bonded polyester and epoxy-mica insulation systems is essentially zero unless the insulation has become saturated with moisture. Older insulation systems, such as asphaltic-mica or shellac mica-folium may have a natural and higher conduction due to the conductivity of the tapes used back of the mica.

The absorption current is made of two components, the polarization of the insulation material and the gradual drift of electrons and ions through the insulating material. The polarization current is cased by the reorientation of the insulating material. This material, usually epoxy, polyester, or asphalt tends to change the orientation of their molecules when in the presence of a direct electric field. It normally takes a few minutes of applied voltage for the molecules to be reoriented, and thus for the current-supplied polarizing energy to be reduced to almost zero. The absorption current, which is the second component, is the gradual drift of electrons and ions through the insulating material. These electron and ions drift until they become trapped at the mica surfaces usually found in rotating insulation systems (Figure 10).

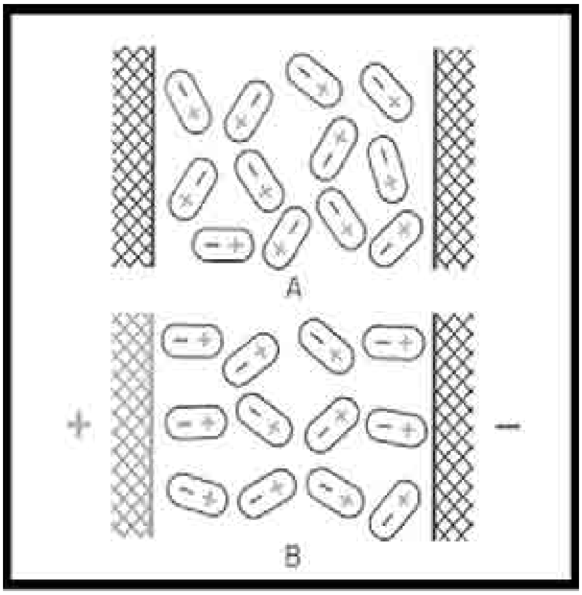


Figure 10

Section A of Figure 10 shows the random orientation of the insulation's molecules. As a direct voltage is applied via the MCE tester, the molecules start to polarize and align, see Section B of Figure 10. The energy required to align the molecules, and subsequently reduce the amount of escaping molecules, is known as absorption current.

Since absorption current is a property of the insulation material and the winding temperature, a specific absorption current is neither good nor bad. The absorption currents will vary from different insulating material. Prior to 1970, older thermoplastic materials used were typically asphalt or shellac, which has a higher absorption current. After 1970, the shift was made to thermalsetting polyester or epoxy bonded insulating material, which significantly decreased the absorption current. Nonetheless, this doesn't mean that the more modern insulating materials are better because they have less absorption current.

The MCE tester measures the sum of all the currents, also called total current and calculates the resistance-to-ground values.

The amount of applied voltage must be appropriate to the nameplate voltage and the basic insulation condition. This is particularly important in small, low-voltage machines where there is only a single layer of insulation. If test voltages are too high, the applied voltage may over stress the insulation. The MCEMAX tester has a low current output. The maximum current output is 1 milliamp, or 1000 microamps, but normally the tester only outputs in the microamp range. This limits the likelihood of insulation damage. See Table 1 for recommended voltage application.

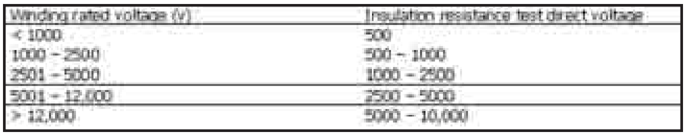
Guidelines for DC Voltages to be Applied During Insulation Resistance Test

REF. IEEE STD. 43-2000

A Rated line-to-line voltage for 3 phase AC machines, line-to-ground voltage for 1-phase machines, and rated direct voltage for dc machines or field windings.

EFFECTS FROM CONTAMINATION

There are many factors that can affect insulation resistance. The surface leakage current is dependent upon foreign matter, such as oil and carbon dust on the winding surfaces outside the stator slot. The surface leakage current may be significantly higher on large turbine generator rotors and DC machines, which have relatively large exposed creepage surfaces.



Winding rated voltage (V)	Insulation resistance test direct voltage
< 1000	500
1000 – 2500	500 – 1000
2501 – 5000	1000 – 2500
5001 – 12,000	2500 – 5000
> 12,000	5000 – 10,000

Table 1

Dust and salts on insulation surfaces, which are ordinarily nonconductive when dry, may become partially conductive when exposed to moisture or oil, and this will cause increased surface leakage current and lower insulation resistance.

The reason a motor's capacitance increases with contamination is because of how a capacitor works. Any two conducting materials, called plates, separated from each other by a dielectric material, form a capacitor. A dielectric material is anything that is unable to conduct direct electric current. A cable or motor winding surrounded by insulation provides one conductor and the dielectric material. The second plate is formed by the stator core and motor casing iron. It is this second plate that is increased in plate size as contamination builds up (Figures 11 and 12).

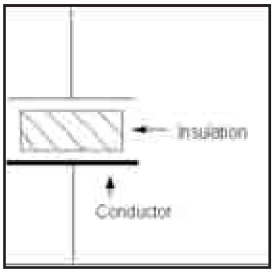


Figure 11

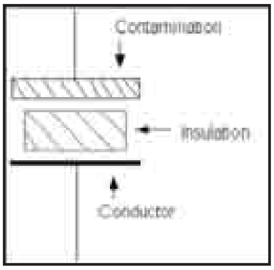


Figure 12

EFFECTS OF TEMPERATURE

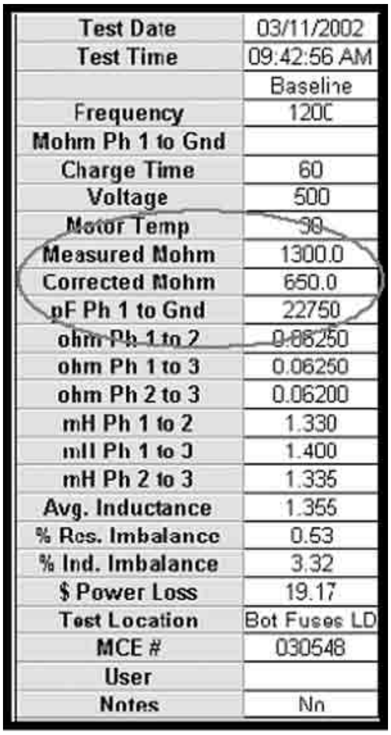
A higher temperature affects the resistance of both the insulation and conductor. There is a term called temperature coefficient (KT). A material has either a positive or negative KT. If the material has a positive KT then, with added heat, the resistance readings will increase. Inversely, if a material has a negative KT, then the resistance readings will decrease with higher temperature. In metals, i.e., the magnetic wire of the stator, higher temperature introduces greater thermal agitation and reduces the movements of free electrons. Because of this reduction in free movement, the resistance readings will increase with added heat and therefore the conductor has a positive KT. However, in insulation, the added heat supplies thermal energy, which frees additional charge carriers and reduces the resistance reading. Therefore, an increase in temperature on insulation reduces the resistance and it is said to have a negative KT. This higher temperature affects every current except the geometric capacitive current.

The recommended method of obtaining data for an insulation resistance versus winding temperature curve is by making measurements at several winding temperatures, all above the dew point, and plotting the results on a semi-logarithmic scale. A semi-logarithmic scale is the same type of scale used to track earthquake activity, called the Richter scale. Earthquake behavior needs to be graphed so that small tremors, as well as a magnitude 9, are still visible on a chart. Nonetheless, the results should plot out to be a straight line.

Since this type of temperature coefficient plotting is usually not feasible, IEEE has developed a corrective rule of thumb. This standard states that to avoid the effects of temperature in trend analysis, subsequent tests should be conducted when the winding is near the same temperature as the previous test. Otherwise the insulation test values are corrected to a common base temperature of 40C.

Therefore, resistance-to-ground (RTG) readings must be temperature corrected for trending and comparison purposes. Temperature correction of the reading is required because the temperature of the insulation system under test may vary depending on operating conditions prior to testing, atmospheric conditions, or ambient temperature. Insulation material has a negative temperature coefficient which means that the resistance characteristics vary inversely with temperature.

In the test setup screen of a Standard test, the temperature of the windings is imputed. The Measured Mohm value is then adjusted to a temperature correction to 40_C. The result is the Corrected Mohm (Figure 13).



Test Date	03/11/2002
Test Time	09:42:56 AM
	Baseline
Frequency	120C
Mohm Ph 1 to Gnd	
Charge Time	60
Voltage	500
Motor Temp	30
Measured Mohm	1300.0
Corrected Mohm	650.0
pF Ph 1 to Gnd	22750
ohm Ph 1 to 2	0.06250
ohm Ph 1 to 3	0.06250
ohm Ph 2 to 3	0.06200
mH Ph 1 to 2	1.330
mH Ph 1 to 3	1.400
mH Ph 2 to 3	1.335
Avg. Inductance	1.355
% Res. Imbalance	0.53
% Ind. Imbalance	3.32
$ Power Loss	19.17
Test Location	Bot Fuses LD
MCE #	030548
User	
Notes	No

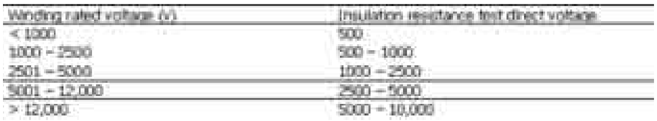
Figure 13

RTG READING

To accurately trend RTG for one motor over time, keep the test voltage and duration of applied voltage constant. The only other factor that will affect the RTG reading is temperature, and therefore it is necessary to correct the temperature in the test setup screen.

IEEE recommended applied voltages can be seen in Table 2.

Guidelines for DC Voltages to be Applied During Insulation ResistanceTest



Winding rated voltage (V)	Insulation resistance test direct voltage
< 1000	500
1000 – 2500	500 – 1000
2501 – 5000	1000 – 2500
5001 – 12,000	2500 – 5000
> 12,000	5000 – 10,000

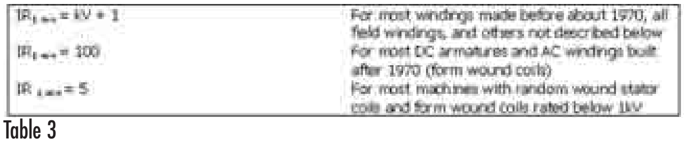
Table 2

REF. IEEE STD. 43-2000

A Rated line-to-line voltage for 3 phase AC machines, line-to-ground voltage for 1-phase machines, and rated direct voltage for DC machines or field windings.

The temperature corrected megohm readings should be recorded and graphed for comparison over time. If a downward trend is observed, look for dirt or moisture. A single reading will not have much meaning in regards to the overall health of the insulation system; a reading as low as 5 megohms may be acceptable if related to a low-voltage application. See Table 3 for recommended minimum insulation resistance.

Recommended Minimum Insulation Resistance Values at 40C
(All values in Mohm)



$IR_{1 min} = kV + 1$	For most windings made before about 1970, all field windings, and others not described below
$IR_{1 min} = 100$	For most DC armatures and AC windings built after 1970 (form wound coils)
$IR_{1 min} = 5$	For most machines with random wound stator coils and form wound coils rated below 1kV

Table 3

CTG READING

During the CTG measurement, the MCE tester applies an AC potential between phase 1 and the ground lead. Circuit capacitance of the insulation system is measured. This capacitance value reflects the cleanliness of the windings and cables. A build-up of contamination on the surface of the windings and cables results in higher capacitance readings.

With a build-up of contamination on the insulation surface, dirty windings and cables produce higher capacitance values than clean ones do. Over time, CTG values steadily increased indicating an accumulation of dirt and that cleaning was necessary. This can be correlated with a lower RTG and higher CTG values.

This is important because dirt and contamination reduce the motor's ability to dissipate heat generated by its own operation, resulting in premature aging of the insulation system. A general rule of thumb is that a motor's life decreases by 50% for every 10^{O}C increase in operating temperature above the design temperature of the insulation system. Heat raises the resistance of conductor materials and breaks down the insulation. These factors accelerate the development of cracks in the insulation, providing paths for unwanted current to flow to ground. The effects from temperature to insulation resistance can be seen in Figure 14.

POLARIZATION INDEX AND DIELECTRIC ABSORPTION

The Polarization Index (PI) and Dielectric absorption (DA) are tests performed by the MCE on a deenergized motor. During the PI and DA tests the MCE tester applies a DC potential between the phase 1 and the ground leads for a pre-determined amount of time, ten minutes for the PI test and 30 seconds for the DA test. During the test, RTG readings are taken every second. Every five seconds the average of the previous five readings is plotted on the RTG (megohms) versus time (seconds) display.

It is not necessary to perform a DA test if you are performing a PI test. When you perform a PI test, WinVis automatically saves the first minute as a DA test and the entire ten minutes as a PI test. When the test is complete, ratios for PI and DA are calculated.

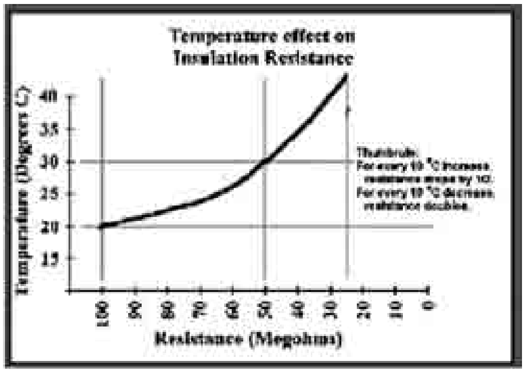


Figure 14

Taking the RTG reading at ten minutes and dividing it by the one minute RTG reading calculates the PI ratio. Taking the RTG reading at one minute and dividing it by the 30 second reading calculates the DA ratio.

PI ratio = 10 min / 1 min
DA ratio = 1 min / 30 sec

The purpose of the PI test is to determine whether or not a motor's insulation system is suitable for operation. The PI test is not limited to AC Induction motors only. It also applies to wound rotor motors, salient pole machines, and certain DC fields. The DC field would have to have conductors that are fully encapsulated in insulation. Therefore, the PI test can be a worthwhile test for multiple type machines.

POLARIZATION INDEX CORRECTION

When performing a PI test, it is not necessary to temperature correct. Since the machine temperature doesn't change appreciably between the one-minute and the ten-minute readings, the effect of temperature on the PI index is usually small. However, if the motor recently shut down and a PI test is performed, the results may be a substantial increase in insulation resistance. This would result in an unusually high PI, at which point additional testing should be performed once the windings have cooled to 40^{O}C or lower.

DATA INTERPRETATION FOR PI AND DA

In Managing Motors Richard Nailen, P.E., offers the following guidelines shown in Table 4, for interpreting PI and DA ratios.

Test	Unacceptable	Acceptable
PI	1 to 1.5	2 to 4
DA	$\leq$ 1.25	$\geq$ 1.50

Table 4

Excellent results should contain a PI ratio of 2–4, achieve higher than minimal RTG, and should be a non-sporadic rise in the megohm reading (Figure 15).

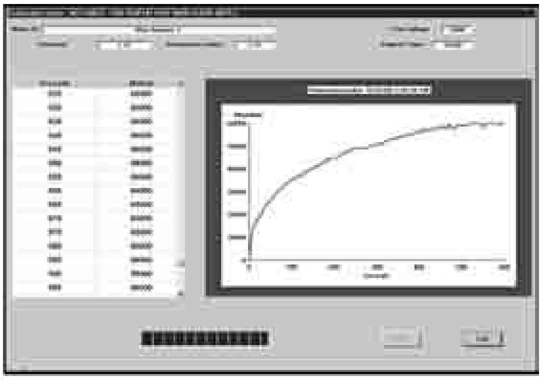


Figure 15

Erratic RTG values occurring at any time during the test is indicative of short-term current transients. These may be due to contamination or moisture. An important aspect in this situation is what level did the RTG values fall to. The IEEE minimum RTG value is 100 Megohm for form wound coils. The RTG values dip below the suggested minimum in Figure 16.

According to the EASA's Principles of Large AC Motors, it states that PI ratios of > 5 should be considered the result of dry or brittle insulation. This may be because of age of the insulation or operating the motor at higher-than-designed temperatures (Figure 17).

PI and DA testing can both be used a single go-no-go, based on the minimum RTG readings established by IEEE 43-2000.

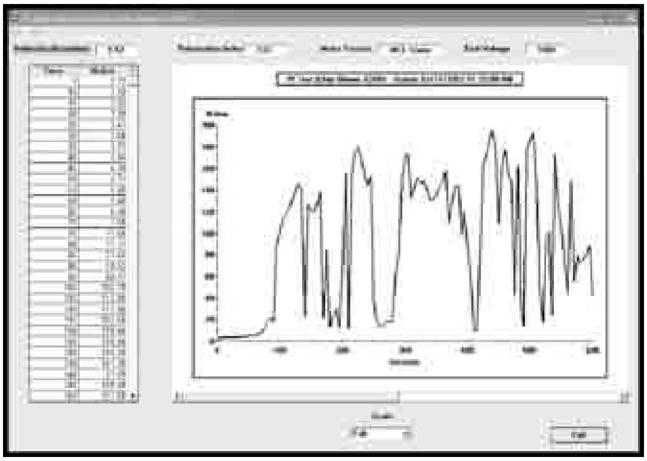


Figure 16

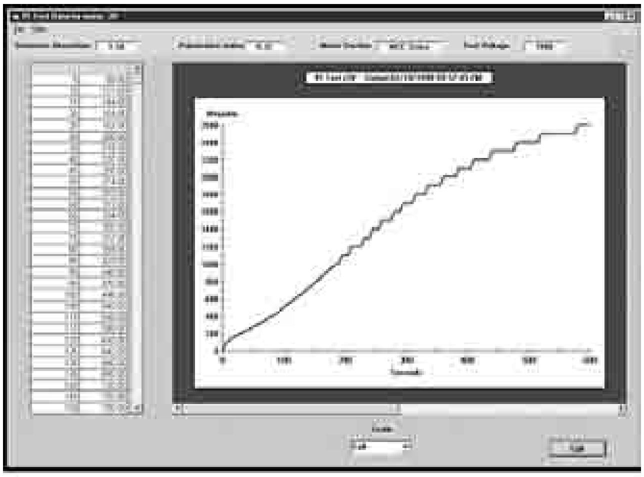


Figure 17

CONCLUSION

Compare the different MCE test results with each other and with other technologies. The more information you have to make a maintenance decision, the more confident you will be about your decision. Use all the technologies to maximize troubleshooting efforts. As other technologies indicate faults, use the MCE to track the changes in motor condition.

PART 4: STATOR

The Stator Fault Zone is often considered one of the most controversial fault zones due to the significant challenge in early fault detection and the prevention of motor failure surrounding the stator windings. This challenge is further intensified in higher voltage machines, where the fault-to-failure time frame becomes much shorter. The Stator Fault Zone is identified as the health and quality of the insulation between the turns and phases of the individual turns and coils inside the motor.

FAILURE MECHANISMS

The likely mechanisms of a stator-winding fault are either a turn-to-turn, phase-to-phase, or turn-to-ground short. A turn-to-turn short is identified as a short of one or more windings in a coil. This can develop into a very low impedance loop of wire, which acts as a shorted secondary of a current transformer. This results in excessive current flow through the shorted loop, creating intense heat and insulation damage. Due to the nature of a random wound design, a shorted turn could occur with much higher impedance, allowing the motor to run for extended periods of time before eventually destroying the coil with the high currents. As a result, it is not unusual to find random wound motors still running with bad stator windings. Form wound coils, however, do not exhibit high turn impedances and will, therefore, heat up quickly following the presence of a turn-to-turn short. A phase-to-phase short is identified as a short of one or more phases to another phase. This fault can be quite damaging due to the possibility of very large voltage potential existing between phases at the location of the short.

ANALYSIS

The big controversy which surrounds the Stator Fault Zone is whether technology can give ample warning of an impending stator winding failure. The big problem with this discussion is often the wording. “Will the MCEMAX find a turn-to-turn short?” is often how this is asked. The real question should be whether a technology can prevent a turn-to-turn short. If you keep a motor long enough, it will develop a turn-to-turn, phase-to-phase, or ground short. The goal of any technology, when faced with this type of long-term certainty, is to identify any conditions, which may be conducive to these faults, so the condition can be corrected. If the conditions conducive to faults are removed, then a longer life for the motor can be expected. If a turn-to-turn short has occurred, there is not a better tool to have than the MCE, which will quickly verify this fault mechanism. Preventing a re-start of the motor may be the best thing at that point in the troubleshooting effort. Again, if you wait until the turn-to-turn short has occurred before you test the motor, you have waited too long.

MCE ANALYSIS

The MCE applies a high frequency AC signal and a low voltage DC signal to the stator windings to perform stator analysis. From these signals, inductance and resistance measurements are taken for comparison between like coils and historical data. If you are testing a three-phase AC induction motor, comparison between the three phases is your most powerful tool. If you are testing a DC motor, then only a single phase exists and comparison to historical test data or identical motors would be effective. Inductance is a highly sensitive parameter and is influenced by many variables within the motor. Rotor condition, air gap flux, frame construction (iron or aluminum), and winding condition are a few of the variables. The most influential variable on the inductance reading is the winding condition. Specifically the number of turns is a squared value in the overall inductance equation as seen below:

L = 0.4pN2mA x 10-8
l

Where: L = inductance in Henrys
N = number of turns of coil
m = permeability of core in electromagnetic units
A = cross-sectional area of core in cm2
l = mean length of core in cm

Although it is our goal to prevent a turn-to-turn short from occurring, you can see that a loss of a single turn in a stator winding will have a dramatic effect on the overall inductance of one or more phases based on the coil configuration. In our effort to identify the conditions that are conducive to a turn-to-turn short, we can use other variables in the equation to identify anomalies, which could create stator problems.

Stator faults often end as a turn-to-turn short, but begin as something else. An example is a motor with excessive vibration, which results in winding movement, friction, and eventually worn insulation between the winding turns. Another example is rotor defects, which create intense heat on the winding surface and eventually create weakened turn insulation or even a ground fault. Core iron defects, such as shorted laminations, will also create additional heat, airflow disturbance, and elevated vibration due to imbalanced magnetic fields and air gap flux. What influence do these situations have on stator inductance? Other than vibration, rotor defects and air gap flux anomalies have a direct impact on the permeability μ of the stator windings. Changes in μ due to a stator core defect will create changes in inductance related to a specific group of coils located near the defect. Changes in μ due to rotor defects will have a varying influence on the stator inductance as the rotor position changes. A quick comparison of the inductance and inductive imbalance values between the three phases or to historical data will indicate changes in these variables and prompt further action or testing to be performed in an effort to prevent the turn-to-turn short.

EMAX ANALYSIS

Stator analysis using EMAX technology is performed by evaluating the phase relationship of voltage and current for each of the three phases of an AC induction motor. These values are used to determine the impedance of each phase and display them as an impedance imbalance. Alarms show if the impedance imbalance exceeds a set point. Any change in the real or reactive component of one phase that is not duplicated on another phase will indicate a change that needs to be investigated.

One of the hurdles involved in this type of testing is acquiring this dynamic data at a load substantial enough to allow these values to be affected by the condition of the windings and not the design. An unloaded motor may run with a current imbalance. This creates variations in the phase impedance, which duplicates indications of a stator fault. Therefore, it is important to have approximately 70% load or more to remove the design impact on these values. Testing should not stop at <70% load, but you must use the test data as comparison values only. A test today at 50-60% load compared to a test last quarter at 50-60% load is still a very informative test. The more test points you acquire, the more confidence you will have in the condition of your stator windings.

Another application of EMAX technology is the ability to acquire data on current through the start-up cycle of the motor. The motor is under the most stress during start-up and can give many indications of problems existing or developing. Stator defects, as in open or shorted turns, will be identified as a change in the amplitude of the in-rush current. The in-rush current is the highest amplitude of current seen through a start-up and occurs immediately after the motor is energized. This occurs due to the effective locked rotor condition, which the motor is in at start-up. Without rotor movement, the counter electromotive force created by the rotor to reduce current flow in the stator does not exist. In fact, the in-rush current immediately following the start of a motor is not affected by load at all. Whether at full load or no load during a start-up, the in-rush current will be the same. Only line voltage and circuit impedance will have an effect on the in-rush current. The current, which exists following the initial in-rush, however, is greatly affected by the load. If only line voltage and circuit impedance will affect the in-rush current value and we generally expect line voltage to be the same, we must rely on circuit impedance as an indicator of stator health. Increased in-rush current results from lower circuit impedance and a decrease in in-rush current results from an increase in circuit impedance. Lower circuit impedance could be caused by weakened turn insulation or shorted turns and an open winding, high resistance connection or even improper repair specifications may cause higher circuit impedance. This is Ohms Law. Remember, significant temperature variations from one test to another will have an impact as well on the overall circuit impedance and should be considered when evaluating the start-up data.

CONCLUSION

Finally, it is important to remember that stator defects do not exist very long before they can become catastrophic. Use all the tools you have available, know the circumstances, and act quickly to dismiss or confirm stator fault indications. Remember, the goal of any technology in stator analysis is to identify any condition which may be conducive to a turn-to-turn short, so that condition can be corrected before a turn-to-turn short occurs.

PART 5: ROTOR

Starting a motor with a broken or cracked rotor bar causes excessive heat to be generated around the vicinity of the broken bar. This can spread to other rotor bars and destroy the insulation around the nearby laminations. It can also affect other parts of the motor. What do we find just a few millimeters away from the rotor? The stator! Stator insulation cannot hold up to the intense heat developed by the broken rotor bar and will eventually fail. Unfortunately, many times broken rotor bars are not easily seen without technology and it may be missed as the root cause of failure. This may result in a motor rewind, and replacement of bearings, but not a rotor repair. When the motor returns to service, it has the same problem all over again, just with new insulation to destroy.

ROTOR DESIGN

The design of the rotor plays a major role in the severity of an identified rotor anomaly. If the rotor is a closed bar design (Figure 17) the severity will be low due to the rotor iron acting to hold the broken rotor bar in place. However, if the rotor is an open bar design (Figure 18) then the severity increases significantly with the identification of a rotor defect. This elevated concern comes from the possibility of the rotor bar squeezing out of the rotor slot and contacting the stator.

TEST METHODS

ROTOR INFLUENCE CHECK

One method of testing the rotor condition is the Rotor Influence Check (RIC). What is a RIC? The RIC is a test performed by the MCE on AC induction, synchronous, and wound rotor motors, which illustrates the magnetic coupling between the rotor and stator. This relationship indicates the condition of the rotor and air gap within the motor.

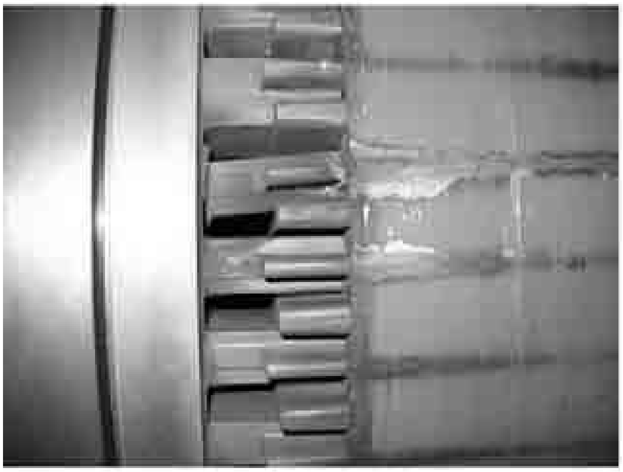


Figure 17

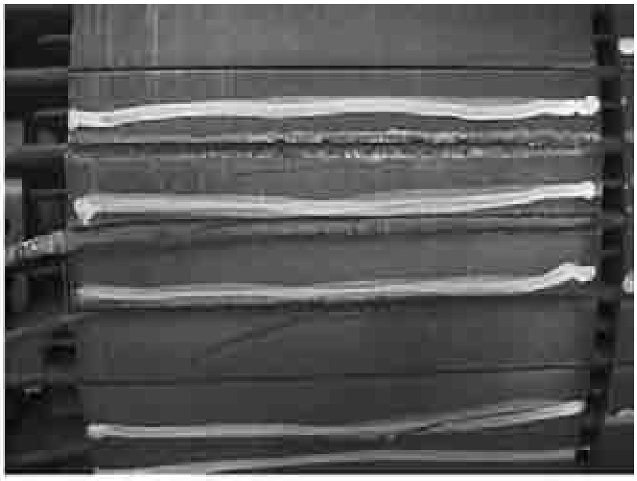


Figure 18

The RIC is performed while rotating the rotor in specific increments (determined by the number of poles) over a single pole group and recording the change in inductance measurements for each phase of a 3-phase motor. For proper resolution, 18 inductance measurements per pole group are recommended. To determine the number of poles in a motor use the following equation.

F = NP / 120

F = Line Frequency (normally 60hz in US)
N = Speed of the motor in RPM
P = # of poles

Recalculated: P = 7200 / RPM

Example: A motor with name plate RPM = 1780 would have how many poles?

P = 7200 / 1780
= 4 poles

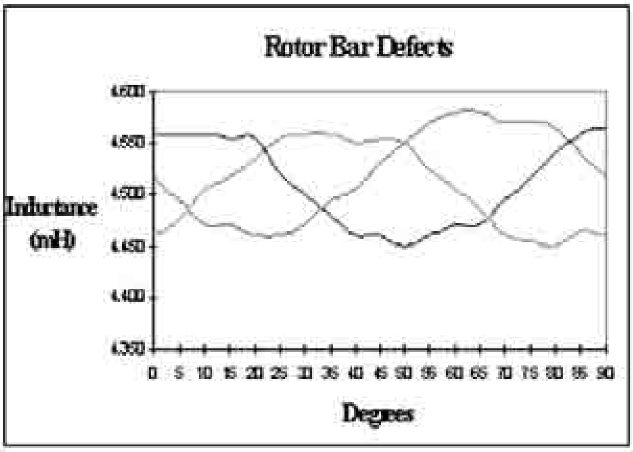


Figure 19

Without historical data, a RIC must be performed to provide any information about the standard squirrel cage induction rotor. Faults such as broken rotor bars or damaged laminations can exist even if the balance of inductance is low. If you are basing the decision to perform a RIC only on how high the balance of inductance is on the baseline test, you could be overlooking late stages of rotor bar defect.

Figure 19 shows the expected inductance changes for a rotor with broken rotor bars. Note the erratic inductance values at the peak of the sine waves for each phase. Broken rotor bars cause a skewing in the field flux generated by and around the rotor bars. A normal rotor would have no skewing or erratic inductance patterns, as seen in Figure 20.

Numerous methods exist for rotor evaluation with the motor running. The EMAX test equipment, using in-rush, time domain, spectral, and demodulated forms of the current signal offer a broad approach to rotor analysis.

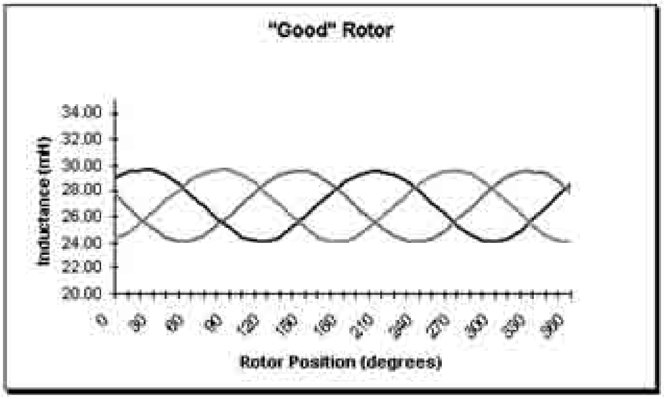


Figure 20

IN-RUSH/START-UP

One method of evaluating rotor health is the In-Rush/Start-Up. Broken rotor bars create higher rotor impedance resulting in higher reflected impedance onto the stator driving the current and torque down. This can be seen in the before and after In-Rush examples in Figure 21.

(FP) SIDEBANDS

Another method is trending the pole pass sideband frequency (Fp) amplitude. Increasing Fp sideband amplitude is

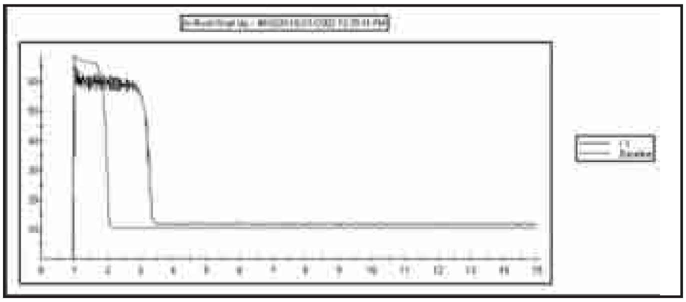


Figure 21

indicative of a modulating line current associated with rotor slip. This modulation is often due to a rotor cage anomaly. Trending the Fp sideband amplitude and determining the differential amplitude as compared to line frequency amplitude allows a predetermined alarm based on well known industry accepted standards. Figure 22 shows an elevated Fp sideband peak above the 36dB differential from line frequency.

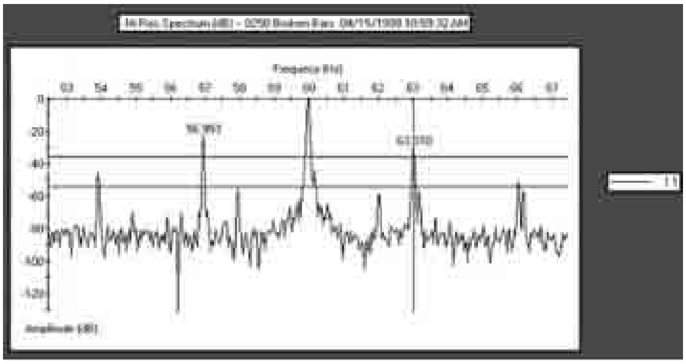


Figure 22

5TH HARMONIC

The third method of evaluating rotor health with the EMAX is the high frequency spectral analysis sometimes referred to as the Swirl Effect. Broken or cracked rotor bars create a phase shift in the air gap flux resulting in multiple Fp sidebands below the end of the 5th harmonic. Figure 23 shows these elevated sidebands beneath the 5th harmonic.

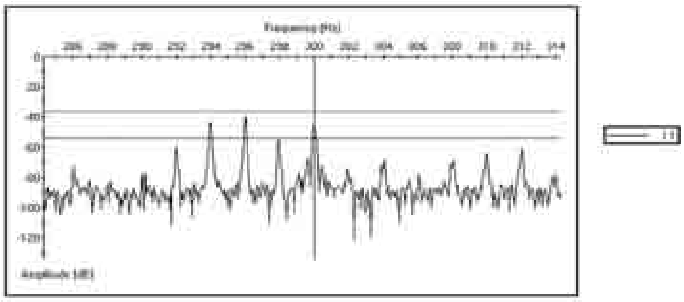


Figure 23

CURRENT DEMODULATION

The fourth method of evaluating rotor health with the EMAX is the demodulated current spectrum. By removing the components of line frequency from the spectrum, the noise floor drops to a value allowing normally non-visible peaks to be visible. Relating to rotor health it also allows a filtered view of the Fp in a demodulated spectrum form. Figure 24 shows the elevated Fp peak exceeding a predetermined alarm set point. This peak was associated with a broken rotor bar in a large 2-pole motor.

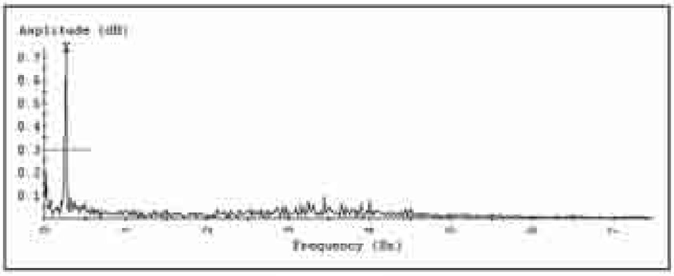


Figure 24

CONCLUSION

In a study funded by the Electric Power Research Institute, 10% of motor failures were caused by a rotor anomaly. This amounts to a large number of motors in even the average-sized plant. It is important to be aware of the rotor design, utilize the broad spectrum of test methods discussed above to correlate and confirm, and extend your motor life by fixing the cause not the symptom.

PART 6: AIR GAP

The Air Gap Fault Zone describes the measurable distance between the rotor and stator within the motor. Air Gap eccentricity is a condition that occurs when there is a non-uniformity in the air gap between the rotor and stator. When there is an eccentricity in the air gap, varying magnetic flux within the air gap will create imbalances in the current flow, which can be identified in the current spectrum. This unevenness in the space between the rotor and stator will affect the alignment of the Rotor Influence Check (RIC) results.

- Static eccentricity occurs when the centerline of the shaft is at a constant offset from the centerline of the stator. An example is a misaligned end bell.
- Dynamic eccentricity occurs when the centerline of the shaft is at a variable offset from the centerline of the stator, such as a wiped bearing.

FAILURE MECHANISMS

By definition, air gap eccentricity is a mechanical fault with the motor. There are several possible causes for the presence of variances in the distance between a rotor and a stator. The five basic types of air gap eccentricities that can occur are:

- Rotor O.D. is eccentric to the axis of rotation
- Stator bore is eccentric
- Rotor and stator are round, but do not have the same axis of rotation
- Rotor and shaft are round, but do not have the same axis
- Any combination of the above

The following are only a few of the possible causes of an air gap eccentricity:

Improper mounting of the motor to its bedplate can lead to an air gap distortion. A loose or missing bolt allows shifting of the motor's mounting foot during thermal expansion of the frame. This shifting over time could lead to a distortion of the frame and possible eccentricity of the stator. The common term for a motor incorrectly mounted is "soft-foot".

During construction of the motor, out-of-roundness of either the rotor or stator will lead to an air gap eccentricity.

Industry standards recommend that measurements for total indicated roundness (TIR) should be performed at different locations along the length of each of these components. Couple these measurements with the circumferences of each component, and depending on the speed and size of the motor, there are recommended tolerances from 5 to 20 percent variation in the air gap.

Eccentricity can develop due to improper tensioning of drive belts coupled to a motor. One customer working with PdMA's technical support staff commented that while they were releasing the tension on one set of belts, they measured the deflection of the motor shaft. The shaft moved over 1/2 of an inch! Improper alignment could also lead to a situation similar to this with both leading to a bowing of the rotor during operation.

Distorted end bells, cocked bearings, or a bent shaft will all cause an air gap eccentricity. During the manufacturing of the rotor, uneven mechanical stresses could be introduced into the cage and lamination stack leading to bowing of the completed rotor.

An air gap eccentricity results in increased levels of vibration due to the uneven magnetic pull it creates between the circumference of the rotor and stator bore. Over time, these elevated levels of vibration can result in excessive movement of the stator winding, which could lead to increased friction and eventually a turn-to-turn, coil-to-coil, or ground fault. Additionally, this vibration can accelerate bearing failure, which could seize the shaft and overheat the windings or allow additional movement of the shaft leading to a rotor/stator rub. The uneven magnetic stresses applied to the rotor coupled with the increased vibration will also contribute to mechanical looseness developing in the rotor. Any of these occurrences could lead to a catastrophic failure of the motor which could require a complete rewind and possible restacking of the iron.

ANALYSIS

The easy part about analyzing a motor for eccentricity is collecting the data. The hardest part seems to be confirming what the data shows and deciding what to do about it. This may be true for many of the fault zones, but there is no absolute standard on how much eccentricity indicated on a current spectrum is too much, with the exception of an actual measurement of the physical air gap. However, once the number of rotor bars is confirmed, PdMA has established guidelines and alarm set points to assist you in making the right decision. The same can be said for the results of a Rotor Influence Check (RIC). The graph indicates the presence of an air gap eccentricity, but without historical results for comparison, you really cannot develop a sense of how much eccentricity has developed and if it is getting worse with time.

MCE ANALYSIS

Eccentricity analysis using the MCE is performed utilizing the RIC test and will be most successfully applied in troubleshooting if pre-existing RIC data is available. However, even without a baseline test, the RIC test will give you definite indications of existing eccentricity.

Analysis of a RIC is done by evaluating the graph of phase-to-phase inductance for the following:

Scale: Sinusoidal Y/N?
Characteristics: Rotor Damage
Alignment: Eccentricity
Peak-to-Peak Inductance: Eccentricity or Stator

Phase-to-phase or turn-to-turn shorts will cause a separation of the three-phase sinusoidal RIC graph. The result is either a "two-up/one-down" or a "one-up/two-down" pattern. The pattern depends on whether the stator windings are wye or delta wound.

Air gap eccentricity impacts the alignment of the graph and the peak-to-peak inductance values of individual phases. Peak-to-peak variations occur on each phase or between phases, depending on the type of eccentricity. If it is static eccentricity, you may get equal peaks from pole group to pole group on the same phase, but the peak amplitude will be quite different between the pole groups of different phases. Simply put, the graph looks misaligned across the graph. If dynamic eccentricity exists, then peaks from pole group to pole group in the same phase will be different. In a 4-pole motor, the rotor is positioned 90 degrees to cover one pole group. When performing a RIC, the WinVis software will use the motor nameplate data to determine the number of poles and then inform the operator how many degrees the rotor needs to be positioned to cover the first pole group.

CONCENTRIC VS. LAP WOUND

An important consideration when evaluating RIC data for indication of eccentricity is whether the motor is concentric or lap wound. If a motor is concentric wound, it is built with a preexisting offset between the stator windings and the rotor.

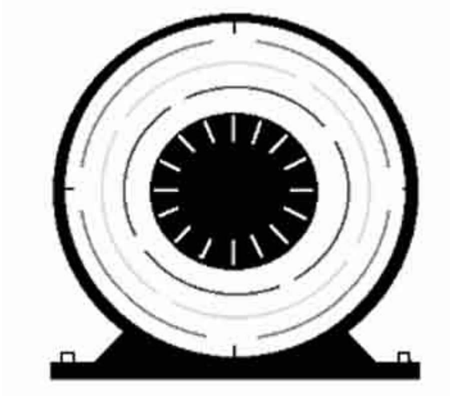


Figure 25

The concentric wound motor seen in Figure 25 has the stator windings inserted into the stator slots in a basket form or stacked configuration. Commonly, all of the pole groups for phase A are laid into the slots, then all of the pole groups for phase B, then finally all of the pole groups for phase C. This results in a greater distance between the rotor and the phase A coils than exists between rotor and phase C coils. This results in a natural stair stepping indication of the phase-to-phase values seen in Figure 26.

Concentric wound motors by design create RIC results that appear as though there may be an eccentricity between the rotor and stator. Results of a RIC performed on a random concentric wound motor can be seen in Figure 26. Notice the peak amplitudes from one pole group to another are basically the same but different from the other two phases. One phase is always slightly lower and the another phase is always slightly higher.

In a case where concentric

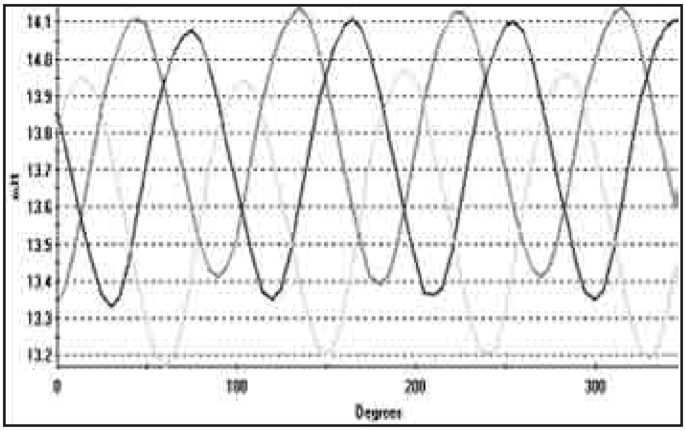


Figure 26

wound motors are identified or suspected, the RIC needs to be performed over two pole faces. Place the motor in observe and confirm any suspected eccentricity with correlating evidence, such as EMAX eccentricity analysis or vibration analysis.

Figure 27 shows an example of a dynamic eccentricity. Notice how the peak amplitudes of the blue phase vary from pole group to pole group as the rotor is rotated. This is occurring for each of the three phases. Dynamic eccentricity is the more severe type of eccentricity due to the increased chance of a rotor/stator rub.

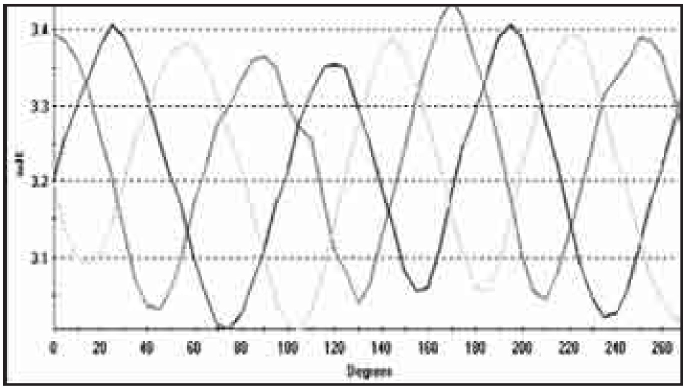


Figure 27

EMAX ANALYSIS

Eccentricity analysis using EMAX technology is performed through a high frequency spectrum of the current signal. When air gap eccentricity exists in a motor, the air gap flux will be off balance, causing different levels of voltage to be induced onto the rotor. This results in irregular current flow on the rotor and varying levels of counter electromotive force, which is felt by the stator. These varying forces on the stator winding produce changes in the amplitude of the current similar to a load change. By displaying the current in a spectrum format, the modulations can be seen as sideband activity around a location known as the Eccentricity Frequency (FECC). The FECC is the number of rotor bars multiplied by the shaft frequency (RPM/60) of the motor. The current modulations are seen as peaks on the spectrum, which will be first and third sidebands of the line frequency powering the motor. In a 60Hz system these peaks will appear as 4 peaks, 120Hz apart, and non-synchronous to line frequency. The peaks are seen in Figure 28.

The large Xs indicate the eccentricity related peaks. The smaller xs indicate harmonics of line frequency. The cursor line located at 1180Hz is the FECC, which is equal to the number of rotor bars times the shaft speed.

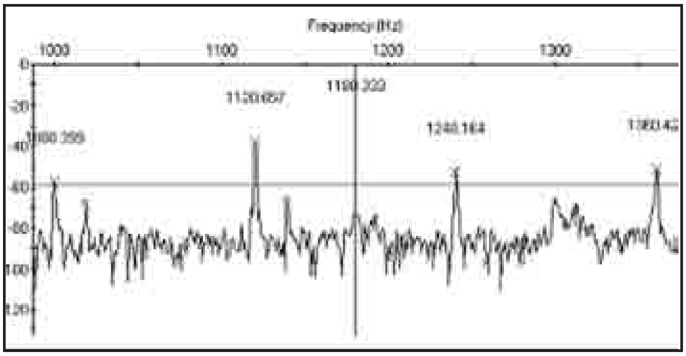


Figure 28

One advantage the EMAX offers is that the technician may use alarm set points to estimate the severity of the eccentricity and act accordingly. However, speed and rotor bar information is necessary for the technician to be able to confirm that the peaks identified on the spectrum are indeed eccentricity related. If the number of rotor bars and the speed are known, the WinVis software automatically places a red X at the four peak locations that identify eccentricity. Obtaining the speed from the Advance Spectral Analysis (ASA) current demodulation software, Low/High Resolution rotor test or via a strobe light is the easy part. The rotor bar count; however, is another matter. First, at the earliest opportunity you should verify that a rotor bar count exists on each of your motor repair specifications. The report you get back from the shop should include how many rotor bars and stator slots exist in the motor. Second, utilize the vibration department to assist in the rotor bar count. They may have previously identified the number of rotor bars through spectrum analysis of the vibration signal.

CONCLUSION

Eccentricities in the air gap will develop uneven magnetic pull between the stator and rotor during operation. This uneven magnetic pull will lead to increased vibration, mechanical wear and tear and, possibly, pullover to the point of a rotor/stator rub. It is important to have equipment which provides you with the necessary information to make informed maintenance decisions concerning the severity of an air gap eccentricity. The MCEMAX provides one easy-to-operate package for the evaluation of air gap eccentricity during operation or when the motor is secured. Giving you the capability to perform a RIC test and eccentricity analysis through the high frequency spectrum of the current signal, the MCEMAX uses a combination of both static and dynamic testing to provide the most comprehensive analysis of the air gap fault zone.

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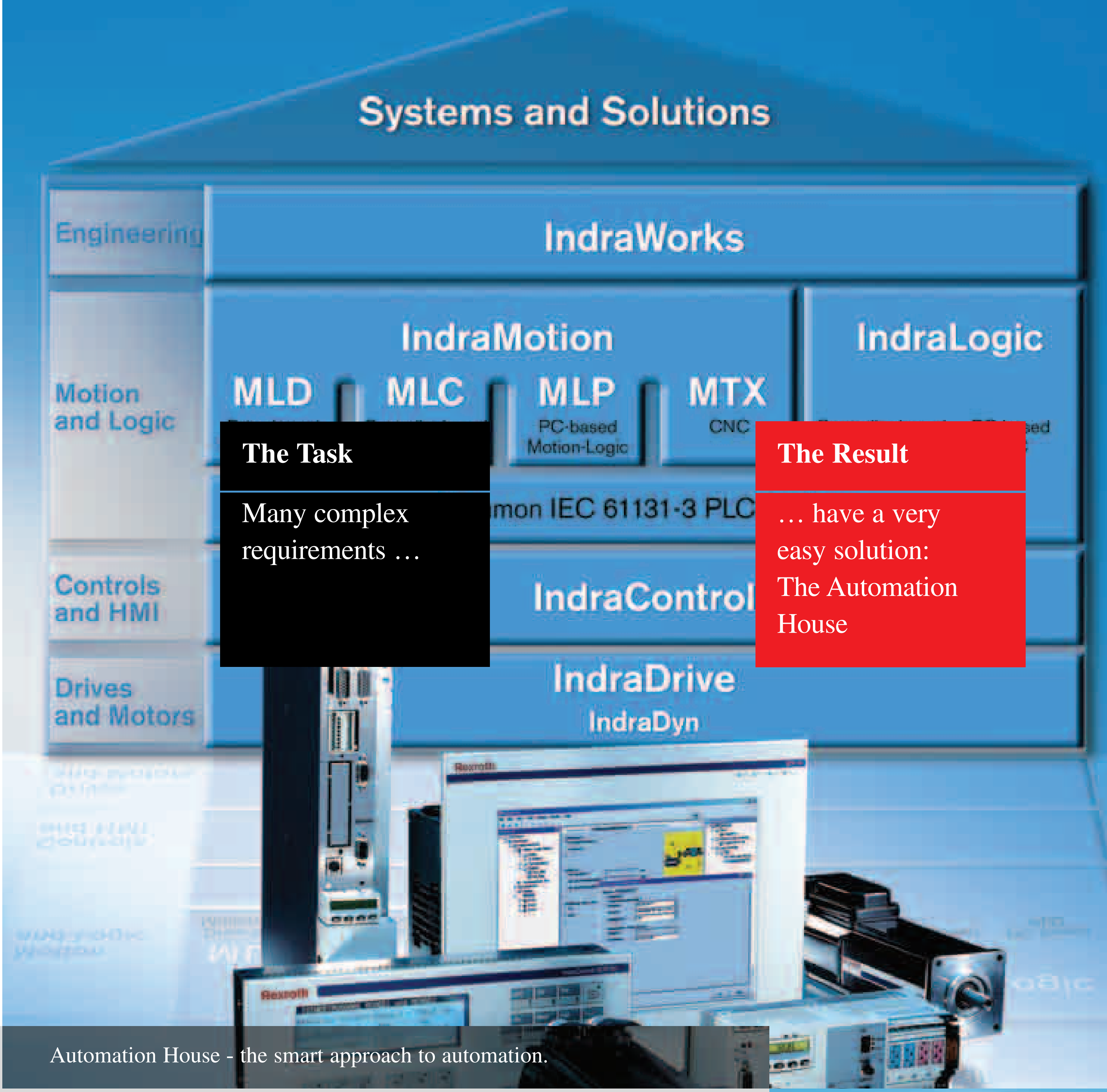

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